Engineering Synthetic Feedback to Promote Recovery of Self-Feeding Skills in People with Sensory Deficits Due to Stroke

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ENGINEERING SYNTHETIC FEEDBACK TO PROMOTE RECOVERY OF SELF-FEEDING SKILLS IN PEOPLE WITH SENSORY DEFICITS DUE TO STROKE

by

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ABSTRACT

ENGINEERING SYNTHETIC FEEDBACK TO PROMOTE RECOVERY
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Kinesthesia refers to sensations of limb position and movement, and deficits of upper limb kinesthetic feedback are common after stroke, impairing stroke survivors' ability to perform the fundamental reaching and stabilization behaviors needed for daily functions like self-feeding. I attempt to mitigate the negative impact of post-stroke kinesthesia deficits by evaluating the utility of vibrotactile sensory substitution to restore closed-loop kinesthetic feedback of the upper limb.

As a first step, this study evaluated performance in healthy individuals during fundamental reaching, stabilization, and tracking behaviors while using supplemental vibrotactile feedback encoding either limb state information or goal-aware error information. First, I determined that performance in reaching and stabilization tasks varies systematically with the amount of limb position and velocity information encoded in limb state feedback and that there is an optimal combination. Next, I compared the utility of optimal limb state to goal-aware error feedback. Both types of feedback reduced error in the reaching and stabilization tasks. Random task-irrelevant sham feedback did not reduce error, demonstrating participants could perceive and understand the information contained within the vibrotactile feedback. Error feedback improved performance more than state feedback; however the relative difficulty of using error feedback outside of a laboratory setting means state feedback should not be discounted. The performance while tracking could not be quantified due to issues with the task design.

As a second step, I performed a series of case studies in five chronic stroke survivors. The stroke survivors all tolerated the vibrotactile feedback well and were able to perceive and understand at least one of the limb state or error feedback encodings. Stroke survivors practiced each information encoding type for one session. During this short period our stroke survivors struggled to integrate visual and vibrotactile inputs and motor control in order to use the vibrotactile information to control the arm. However, two additional practice sessions with error feedback for one participant led to a two thirds reduction in reaching error. These results suggest stroke survivors can learn to use supplemental vibrotactile feedback to enhance control of the contralesional arm.

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Chapter 1: Introduction

1.1 Rationale and Specific Aims

Kinesthesia refers to sensations of limb position and movement (Bastian 1887) derived predominantly from information encoded by muscle spindle afferents (c.f., Proske and Gandevia 2012), which are sensitive to muscle length and rate of length change (Edin and Valbo, 1990). Deficits of kinesthetic feedback are common after stroke. Almost 50% of stroke survivors experience impaired limb position sense in their contralesional arm (Carey and Matyas 2011; Dukelow et al. 2010; Connell et al. 2008). Loss of kinesthetic sensation contributes to impaired control of reaching and stabilization behaviors (Scheidt and Stoeckmann 2007; Zackowski et al. 2004) that are vital to an independent life style (Blennerhassett et al. 2007; Tyson et al. 2008) and basic daily functions such as self-feeding. Although people suffering loss of kinesthetic feedback can move by relying on vision of their limbs, long processing delays inherent to the visual system (100-200 ms; Cameron et al. 2014) yield movements that are typically slow, poorly-coordinated, and require great concentration (Sainburg et al. 1993; Ghez et al. 1995). Visually guided corrections come too late and result in jerky, unstable movements (Sarlegna 2006). Unfortunately, many stroke survivors give up using their contralesional limb because of their sensorimotor deficits (Taub et al. 1993) even though this reduces quality of life (Abela et al. 2012; Tyson et al. 2008). Most therapies target motor retraining, without focusing on the critical interactions of sensory and motor systems. Developing techniques to address impaired kinesthesia sensation could lead to both motor and sensory interventions that together could improve the sensorimotor function of stroke survivors.

The long-term goal of the work presented here is to mitigate the negative impact of post-stroke kinesthesia deficits by creating sensory substitution technologies that provide real-time feedback of contralesional arm state (e.g., the position and velocity of the hypoesthetic arm and hand) to a site on the body retaining somatosensation (e.g., the ipsilesional arm). The idea of providing supplemental feedback to mitigate sensory deficits has been explored for many decades (c.f., White et al. 1970). Successful applications have been developed using a variety of feedback methods, including vibrotactile feedback, however shortcomings include a lack of focus on limb kinesthesia and the use of feedback systems that interfere with daily functions like eating and verbal conversation (e.g., in systems that use electrotactile stimulation of the tongue; c.f., BrainPort, WiCab, Inc.). We therefore propose to use vibrotactile stimulation of one arm to deliver supplemental kinesthetic feedback pertaining to motion of the other arm as a way to provide feedback while avoiding disruption of daily living functions like speech or sight.

There are many conceivable ways to encode information about a moving limb within a vibrotactile feedback stream, and it is unclear which way might best facilitate closed-loop control of goal-directed stabilizing and reaching behaviors. One possibility is the encoding of limb state (e.g., the position and/or velocity of the moving limb). A second distinct approach, "goal-aware" feedback (Tzorakoleftherakis et al. 2016), additionally encodes information about the current task's objectives. For example, error feedback, a simple form of goal aware vibrotactile feedback indicates the instantaneous error between the hand's current position and the position of a visual target. Each encoding scheme might offer distinct advantages in terms of user performance and practicality.

As a first step toward the larger goal of reducing the negative impact of post-stroke kinesthesia deficits, this study tested the ability of people with no known neuromotor deficits to control goal-directed actions using various supplemental vibrotactile stimuli that provided real-time feedback about the moving arm to the other arm. We focused on reaching, stabilizing, and tracking actions that are fundamental building blocks for many activities of daily living. It is well known from the motor control literature that healthy human participants generate systematic performance errors in the absence of ongoing visual feedback of reaching and stabilization behaviors (e.g. proprioceptive drift) (Wann and Ibrahim, 1992; Scheidt et al., 2005; Smeets et al. 2006; Suminski et al., 2007). We compared the extent of performance improvements (i.e., reduction in proprioceptive drift) when participants were provided supplemental vibrotactile state feedback vs. error feedback. As a second step, this study conducted a set of case studies examining the extent to which stroke survivors could use (and learn to use) supplemental vibrotactile feedback to enhance control of the contralesional arm.

Our big-picture hypothesis proposes that by using task-relevant vibration signals as a sensory substitution method, it may be possible to enhance or restore closed loop kinesthesia feedback in stroke survivors suffering from impaired kinesthetic sense – but retain some residual motor capacity - in the contralesional arm and hand. By developing a method to reduce the impact of impaired kinesthesia, we seek to improve functional outcomes for stroke survivors meeting this pattern of sensorimotor deficits. Here, as a first step toward that goal, I investigate synthetic vibratory feedback as a sensory substitution method to compensate for inherent limitations of kinesthetic feedback in healthy human participants. By doing so, this study will identify what types of information are useful for encoding supplemental kinesthetic feedback. We will also investigate the performance benefits conferred by vibrotactile feedback in a small cohort of stroke survivors. Three specific aims are addressed.

1. Determine if the performance of healthy participants during reaching and stabilization tasks varies systematically with the amount of limb position or velocity information encoded in synthetic vibrotactile feedback, in order to identify the optimal combination of limb position and velocity information.
2. Compare the performance of healthy participants conducting reaching and stabilization tasks in the absence of vision with three different types of vibration encodings – optimal limb state feedback (containing both position and velocity information), goal-aware hand position error feedback, or task-irrelevant random sham feedback.
3. Perform a series of case studies, wherein stroke survivors attempt to use supplemental kinesthetic feedback to improve performance of reaching and stabilization behaviors performed with the contralesional arm.

In the course of conducting these three aims, this study seeks to provide guidance for the future development of vibrotactile sensory substitution devices for stroke survivors.

1.2 Outline of the thesis

This first chapter has presented a rationale for the study and a description of its specific Aims. Chapter 2 will present a review of pertinent literature. Chapter 3 presents the primary experimental study, which has been submitted to the Journal of Neuroengineering and Rehabilitation, and is currently in revision. Chapter 4 presents an initial attempt to examine the extent to which supplemental kinesthetic feedback can enhance the control bandwidth of the arm in the absence of ongoing feedback of concurrent visual feedback of performance. Chapter 5 presents results from five case studies in stroke survivors. Finally, Chapter 6 presents overall conclusions and suggestions for future work.

Chapter 2: Background

2.1 Proprioception and arm control in neurologically-intact individuals

We justify first studying technologies intended for stroke survivors in neurologically intact people by noting that the vast majority of people – including neurologically intact individuals - exhibit imperfect somatosensory control of the arm and hand in the absence of ongoing visual feedback. Indeed, the most conspicuous and ubiquitous manifestation of imperfect somatosensation is "proprioceptive drift" (Wann and Ibrahim 1992; c.f., Smeets et al. 2006), wherein marked errors in the perceived position of the unseen hand develop within a period of 12 to 15 seconds (Paillard and Brouchon 1968). Proprioceptive error is likely due to a progressive drift between visual and proprioceptive maps of body configuration when vision of the relative positions of the body and the visual target is precluded (Jeannerod 1989).

For example, in the study by Wann and Ibrahim (1992) participants were asked to track a moving visual target with a fingertip of their visually occluded dominant arm for 150 seconds. Every 15 seconds, the participant was asked to use their non-dominant hand to match the location of their dominant hand fingertip to fingertip. In some trials, frequent brief glimpses of the tracking dominant arm were periodically provided. In other trials, there was never any visual feedback of the tracking arm. In both cases, a 1.6 cm error developed within the first 15 seconds of the trial. In trials with brief glimpses of the arm, no further error accumulated after the first glimpse of the arm at 15 seconds. However, in trials without any visual feedback of the arm, error continued to linearly accumulate until the trial completed 150 seconds later. Wann and Ibrahim suggest these results are best explained if the proprioception and vision spatial maps naturally drift apart if they are not activated simultaneously. Thus, proprioceptive drift occurs naturally in neurologically intact participants when they do not receive frequent visual glimpses of the arm. This naturally occurring proprioceptive error offers a model for impaired kinesthesia in stroke survivors.

2.2 Control actions in neurologically-intact individuals

Goal-directed behaviors like reaching and stabilizing the hand against environmental perturbations may invoke at least two different and independent types of control actions: trajectory control and end point stabilization (Scheidt and Ghez, 2007). Different tasks might differentially exploit either control action. A stabilization task, in which participants must remain at a location despite perturbations, requires primarily the end point stabilization control action. A tracking task, in which participants must follow a moving target, requires primarily trajectory control. A reaching task, in which participants must reach to and end on a target, requires both trajectory control and end point stabilization control actions. Both of these control actions are affected by proprioceptive drift, which succinctly predicts the pattern of performance errors observed during goal-directed reaching (Scheidt et al. 2005) and stabilizing actions (Suminski et al. 2007) performed with the hand in the absence of visual feedback.

2.3 Vibrotactile sensation in neurologically-intact individuals

Vibration of hairy skin is thought to be sensed primarily by at least two types of receptors; shallow rapidly-adapting mechanoreceptors (RA) and deeper Pacinian corpuscles (PC) (Bensmaia and Hollins, 1999; Mahns et al., 2005; Mountcastle et al., 1972; Bolanowski et al., 1988). The RA channel is located superficially in the skin, as they may be compromised by the administration of local skin anesthesia. The PC channel is located deeper in the skin and, particularly in hairy skin, tissues below the skin and is not compromised by local skin anesthetic. RA respond to lower frequency vibrations (<80Hz) while the PC responds to higher frequency vibrations (>30Hz). Sensation of the area of frequency overlap in the middle appears to use some combination of RA and PC receptors, as this sensation is somewhat affected by anesthesia. Pattern discrimination and the minimum amount of detectable change in vibration intensity are thought to be better sensed in the RA than the PC (Bensmaia and Hollins, 1999; Mountcastle et al., 1972). Tannan et al. (2006) also report that adaptations in the RA channels within the first few seconds of exposure to low frequency vibration (25Hz) causes an increase in localization ability.

2.4 Multisensory Integration in neurologically-intact individuals

During simple interactions with the environment, such as picking up a ringing phone, a person receives a number of sensory inputs about the phone in a variety of relative reference frames (Shadmehr and Wise, 2005). The visual system provides information about the position of the phone, the position of nearby objects, and the position of the hand reaching towards the phone, in eye-centered coordinates. The proprioceptive system provides information about the speed and location of the arms as they reach, in joint space coordinates. The auditory vestibular system provides information about the location of the ringing phone from the orientation and the tilt of head, which is affected by the direction of the gaze and the balance of the individual. Information from all three senses, and their respective reference frames, is combined to provide an accurate location of the phone and the limb so that the person can successfully interact with the object (Shadmehr and Wise, 2005). Each sensory input is thought to be weighted reflecting the accuracy and reliability of each sense in the current context and a Bayesian framework allows for more optimal results as opposed to, for example, a simple averaging of the various sensory inputs (Deneve and Pouget, 2004; Van Beers et al. 1999; Shadmehr and Wise, 2005). Importantly, research suggests that one sensory modality can be mapped into the reference frame of another sensory modality (Deneve and Pouget, 2004; Shadmehr and Wise, 2005). In this way, one sense can be used to inform another sense. For example, one can still pick up their phone in the dark with poor visual cues because the auditory information from the ringing can fill in for the missing visual input of the position of the phone and the proprioceptive information can fill in for the missing visual input of the motion of the hand. In this same way, the participant can similarly still complete the task with impaired proprioception (as often happens in, for example, stroke), or with poor audition (such as in a noisy environment). Because one sense can fill in and substitute for another, this scheme allows for supplemental sensory substitution as a compensatory technique.

2.5 Vibrotactile feedback for sensory substitution

The idea of providing supplemental feedback to mitigate sensory deficits has been explored for many decades (c.f., White et al. 1970). Successful applications include cochlear implants (c.f., Loeb 1990) and non-invasive systems that encode video images into either vibratory or electrical signals applied to the skin at one of several body parts (abdomen, back, thigh, fingertip, forehead, tongue) (Kaczmarek et al. 1991). Vibrotactile systems for enhancing postural stabilization in vestibular patients have been proposed (Sienko et al. 2008; Lee et al. 2012) and show promise (Peterka et al. 2006) when the synthesized feedback includes all task-relevant states (Lee et al. 2011). Vibration tolerability tests in stroke survivors show comfort and acceptance of vibration without anxiety or negative complications (Bento et al., 2012). Vibrotactile systems also show promise for providing information about grasp force and hand aperture to users of myoelectric forearm prostheses (Witteveen et al. 2014).

As an example of the potential of vibrotactile feedback systems, a recent study has described a vibrotactile arm band that is able to reduce arm angle error while teaching rehabilitative motor skills (Bark et al. 2015). This device was developed to aid physical therapists in providing feedback to stroke survivors during motor rehabilitation wherein the patient repetitively practices a series of movements. 4 vibrotactile motors were placed around the arm at the bicep and 4 vibrotactile motors were placed around the arm at the wrist. A Microsoft Kinect 360 was used to track the user's arm motion and provide feedback about the error of each arm segment, intended to mimic the motion corrections a physical therapist would deliver through light touch. Only one vibration motor was ever active at a time and delivered repulsive vibrotactile cues. Visual feedback was provided on a computer monitor in the form of an avatar that tracked the user's motion and an avatar which displayed the target motion. 26 participants attended for 4 consecutive sessions in which they practiced 6 arm motions using either only visual feedback (V) or visual feedback with vibrotactile feedback (VT). The arm motions tested between 1 and 3 degrees of freedom.

The results of Bark et al.'s study shows that the arm angle errors for 1 degree of freedom movements were significantly lower when participants used vibrotactile feedback and visual feedback (VT) instead of just visual feedback (V). There was no effect of vibrotactile feedback on 2 or 3 degree of freedom arm motions. Work load surveys after each session indicate participants experienced a higher workload when using both visual and vibrotactile feedback (VT) as compared to visual feedback alone (V). In both cases the work load significantly decreased across sessions. 18 of the 26 participants indicated they preferred to practice the arm motions with both visual and vibrotactile feedback (VT) rather than with visual feedback alone (V). Altogether, this study shows the vibrotactile feedback can help neurologically intact participants learn simple rehabilitative arm motions. Despite the higher workload involved in learning the arm motions when vibrotactile feedback was present, most participants preferred to practice the arm motions with the vibrotactile feedback instead of without it.

While these past works reveal the brain's remarkable ability to integrate synthetic feedback for perception and control, shortcomings include a lack of focus on limb kinesthesia, use outside of the clinic, and use of feedback systems that interfere with daily functions like eating and verbal conversation (e.g., devices using electrotactile tongue stimulation; c.f., BrainPort, WiCab, Inc.). We therefore propose to use vibrotactile stimulation of one arm to deliver supplemental kinesthetic feedback pertaining to motion of the other arm. We rationalize this choice because, aside from the palms and fingers, tactile feedback from the surface of the arm does not appear to be critically important for completing most daily living activities and thus, we minimize the likelihood that the vibrotactile display would impede use of the stimulated arm for other tasks.

2.6 Encoding information in vibrotactile feedback

There are many conceivable ways to encode information about a moving limb within a vibrotactile feedback stream, and it is unclear which way might best facilitate closed-loop control of goal-directed stabilizing and reaching behaviors. One possibility is the encoding of limb state (e.g., the position and/or velocity of the moving hand). From the perspective of technological implementation, the hardware and software tools needed to develop stand-alone wearable technologies capable to detect, synthesize and deliver limb state information in unconstrained environments are readily available. A second, distinct approach, "goal-aware" feedback (Tzorakoleftherakis et al. 2016), additionally encodes information about the current task's objectives. For example, a simple form of goal aware vibrotactile feedback might indicate the instantaneous error between the elbow’s current position and the target elbow position, as used in Lieberman et al. (2015). In that study, participants received vibrotactile feedback of joint angle error by four tactors placed around the wrist and four tactors placed around the elbow. A computer screen provided visuals of several discrete arm positions that together composed a target arm motion. The vibrotactile signal was proportional to the degrees of error between the user’s joint angle and the target joint angle at each discrete step of the motion. Participants were able to reduce joint angle error by 27% using the joint angle error feedback as compared to attempting the task without any vibratory feedback.

Alternatively, a more complex form of goal aware feedback might encode information about which direction to move the arm, based on the output of a computational model implementing an optimal trade-off between kinematic and energetic performance, as used in Tzorakoleftherakis et al.. In that study, participants attended for one session in which they attempted to balance a one degree of freedom virtual inverted pendulum on a cart. Two vibrotactile motors were applied to the right thumb and little finger. Movement of the right hand produced movement of the cart in the same direction. The vibrotactile motors encoded a real-time “teaching” signal instructing the participant which direction they must move their hand (and thus the cart) in order to stabilize the inverted pendulum. Participants competed the task using only visual feedback (V), only vibrotactile feedback (T), or both visual and vibrotactile feedback (VT). Without participant intervention, the pendulum would naturally fall within about 5 seconds. When the participant practiced the task with only visual feedback (V), the average time to failure was 13 seconds. The average time to failure with only vibrotactile feedback (T) was 9 seconds; participants were not as good as with visual feedback (V), but were able to keep the pendulum upright for several seconds. However, when participants used both visual and vibrotactile feedback (VT), they were able to maintain the inverted pendulum for an average of 37 seconds. In addition, a large standard deviation for this condition suggests that participants were still learning how to best use the dual-feedback, and could improve with further practice.

Although goal-aware feedback might yield better performance than limb state feedback because it includes additional task-specific information, this approach suffers from a number of unique technological challenges that state feedback avoids. In particular, determining the user's motor intentions and movement goals from one moment to the next in a dynamically changing or uncontrolled environment seems to be a daunting undertaking. Inaccuracies in estimating intent would lead to unreliable feedback, thus compromising usability of the vibrotactile display.

Human physiology provides no clear guidance on how kinesthetic information might be encoded within supplemental vibrotactile feedback to optimize augmented closed-loop control of stabilization and reaching behaviors. For example, muscle spindle primary endings encode muscle length and the rate of length change in a joint-based coordinate reference frame whereas muscle spindle secondary endings encode primarily muscle length information (Proske and Gandevia 2012). Simulated vibrotactile limb state feedback could readily emulate these types of native feedback. By contrast, Golgi tendon organs encode muscle tension (Proske and Gandevia 2012), which may be more difficult to estimate and emulate. Additionally, γ-motor neurons can modulate the sensitivity of muscle spindles in ways that are - in some cases - suggestive of error encoding (Houk and Rymer 1981), although the functional dependence of spindle feedback on γ-motor neuron activity is rather complex (Grillner 1969).

Chapter 3: Optimizing vibrotactile feedback to enhance real-time control of the arm during reach and stabilization tasks: An article submitted to the Journal of Neuroengineering and Rehabilitation

3.1 Background

Kinesthesia refers to sensations of limb position and movement (Bastian 1887) derived predominantly from information encoded by muscle spindle afferents, which are sensitive to muscle length and rate of length change (c.f., Proske and Gandevia 2012). Deficits of kinesthetic feedback are common after stroke. Almost 50% of stroke survivors experience impaired limb position sense in their contralesional arm (Carey and Matyas 2011); Dukelow et al. 2010; Connell et al. 2008). Loss of kinesthetic sensation contributes to impaired control of reaching and stabilization behaviors that are vital to an independent life style (Blennerhassett et al. 2007; Scheidt and Stoeckmann 2007; Tyson et al. 2008; Zackowski et al. 2004). Although people suffering loss of kinesthetic feedback can move by relying on vision of their limbs, long processing delays inherent to the visual system (100-200 ms; Cameron et al. 2014) yield movements that are typically slow, poorly-coordinated, and require great concentration (Sainburg et al. 1993; Ghez et al. 1995). Visually guided corrections come too late and result in jerky, unstable movements (Sarlegna 2006). Unfortunately, many stroke survivors give up using their contralesional limb because of their sensorimotor deficits (Taub et al. 1993) even though this reduces quality of life (Abela et al. 2012; Tyson et al. 2008).

Our long-term goal is to mitigate the negative impact of post-stroke kinesthesia deficits by creating sensory substitution technologies that provide real-time feedback of contralesional arm state (e.g., the position and velocity of the insensate arm and hand) to a site on the body retaining somatosensation (e.g., the ipsilesional arm). As a first step, the current study tested the ability of people with no known neuromotor deficits to control goal-directed actions using supplemental vibrotactile stimuli that provided real-time feedback about the moving limb to a part of the body that was not itself involved either in the movement or in essential behaviors like speaking and eating. We justify this approach by noting that the vast majority of people – including neurologically intact individuals - exhibit imperfect somatosensory control of the arm and hand in the absence of ongoing visual feedback. Indeed, the most conspicuous and ubiquitous manifestation of imperfect somatosensation is "proprioceptive drift" (Wann and Ibrahim 1992; c.f., Smeets et al. 2006), wherein marked errors in the perceived position of the unseen hand develop within a period of 12 to 15 seconds (Paillard and Brouchon 1968). Proprioceptive error is likely due to a progressive drift between visual and proprioceptive maps of body configuration when vision of the relative positions of the body and the visual target is precluded (Jeannerod 1989). Proprioceptive drift succinctly predicts the pattern of performance errors observed during goal-directed reaching (Scheidt et al. 2005) and stabilizing actions (Suminski et al. 2007) performed with the hand in the absence of visual feedback.

The idea of providing supplemental feedback to mitigate sensory deficits has been explored for many decades (c.f., White et al. 1970). Successful applications include cochlear implants (c.f., Loeb 1990) and non-invasive systems that encode video images into either vibratory or electrical signals applied to the skin at one of several body parts (abdomen, back, thigh, fingertip, forehead, tongue) (Kaczmarek et al. 1991). Vibrotactile systems for enhancing postural stabilization in vestibular patients have been proposed (Sienko et al. 2008; Lee et al. 2012) and show promise (Peterka et al. 2006) when the synthesized feedback includes all task-relevant states (Lee et al. 2011). Vibrotactile systems also show promise for providing information about grasp force and hand aperture to users of myoelectric forearm prostheses (Witteveen et al. 2014). While these past works reveal the brain's remarkable ability to integrate synthetic feedback for perception and control, shortcomings include a lack of focus on limb kinesthesia and use of feedback systems that negatively impact quality of life (e.g., by interfering with verbal conversation; c.f., BrainPort, WiCab, Inc.). We therefore propose to use vibrotactile stimulation of one arm to deliver supplemental kinesthetic feedback pertaining to motion of the other arm. We rationalize this choice because, aside from the palms and fingers, tactile feedback from the surface of the arm does not appear to be critically important for completing most daily living activities and thus, we minimize the likelihood that the vibrotactile display would impede use of the stimulated arm for other tasks.

There are many conceivable ways to encode information about a moving limb within a vibrotactile feedback stream, and it is unclear which way might best facilitate closed-loop control of goal-directed stabilizing and reaching behaviors. One possibility is the encoding of limb state (e.g., the position and/or velocity of the moving hand). From the perspective of technological implementation, the hardware and software tools needed to develop stand-alone wearable technologies capable to detect, synthesize and deliver limb state information in unconstrained environments are readily available. A second, distinct approach, "goal-aware" feedback (Tzorakoleftherakis et al. 2016), additionally encodes information about the current task's objectives. For example, a simple form of goal aware vibrotactile feedback might indicate the instantaneous error between the hand's current position and the position of a visual target. A more complex version might encode information about which direction to move the arm, based on the output of a computational model implementing an optimal trade-off between kinematic and energetic performance. Although goal-aware feedback might yield better performance than limb state feedback because it includes additional task-specific information, this approach suffers from a number of unique technological challenges that state feedback avoids. In particular, determining the user's motor intentions and movement goals from one moment to the next in a dynamically changing environment seems to be a daunting undertaking. Errors in estimating intent would lead to unreliable feedback, thus compromising usability of the vibrotactile display.

Human physiology provides no clear guidance on how kinesthetic information might be encoded within supplemental vibrotactile feedback to optimize augmented closed-loop control of stabilization and reaching behaviors. For example, muscle spindle primary endings encode muscle length and the rate of length change in a joint-based coordinate reference frame whereas muscle spindle secondary endings encode primarily muscle length information (Proske and Gandevia 2012). Simulated vibrotactile limb state feedback could readily emulate these types of native feedback. By contrast, Golgi tendon organs encode muscle tension (Proske and Gandevia 2012), which may be more difficult to estimate and emulate. Additionally, γ-motor neurons can modulate the sensitivity of muscle spindles in ways that are - in some cases - suggestive of error encoding (Houk and Rymer 1981), although the functional dependence of spindle feedback on γ-motor neuron activity is rather complex (Grillner 1969).

The ultimate objective of this line of work is to develop sensory substitution technologies that enhance closed-loop control of goal-directed behaviors in people with impaired somatosensation. The basic idea is to bypass injured feedback control pathways by encoding information about a moving limb (e.g., the dominant arm) into a vibrotactile feedback stream applied to a non-moving body part (e.g., the non-dominant arm) to enhance performance of goal-directed behaviors performed in the absence of ongoing visual feedback. To see how this might work, consider a simplified, single-joint model of a human-in-the-loop state feedback control system (Fig 3.1A). Although this model is not intended to replicate the complexities of human sensorimotor control [for example see (Heenan et al. 2014)], it includes many characteristics relevant to the current problem: a "limb" dominated by viscoinertial dynamics; feedback delay arising from sensory transduction, transmission and processing; and a central mechanism that transforms performance errors into corrective motor commands, modeled here using the simplest control law: proportional control. We justify use of the simplest control law for the controller because we ultimately seek to design a sensory substitution system that requires minimal information processing by the stroke-injured brain.

Feedback in the model can simulate visual or proprioceptive feedback by adjusting the sensor function to emulate physiological systems. Emulating visual feedback uses position feedback in the sensor function ($\theta_f = \theta_a$) to represent the type of information that feeds into saccadic eye movements that provide information about object location in space (Biguer et al, 1982). The visual feedback used in this model represents position-based saccadic movements, since the goal position is static, rather than velocity-based smooth pursuit movements, which are used for moving targets. Emulating proprioception uses both position and velocity feedback in the sensor function ($\theta_f = \theta_a + 0.15\ d\theta_a /dt$) to represent physiological feedback from the muscle spindle primaries and secondaries.

From the perspective of feedback control engineering, adding velocity information to the feedback pathway has a similar effect on the overall feedback transfer function as adding derivative control action to the controller. For example, compare the transfer functions for the proportional controller with only position feedback ($H_1(S)$), proportional controller with position plus derivative feedback ($H_2(S)$), and a proportional plus derivative controller with only position feedback ($H_3(S)$) (K is some constant) (Equations 1):

$$H_1(S) = \frac{\varphi}{s^2+3s+\varphi K_p} \quad [1a]$$

$$H_2(S) = \frac{\varphi}{s^2+(3+\varphi K_d)s+\varphi K_p} \quad [1b]$$

$$H_3(S) = \frac{K_{cd}s+\varphi}{s^2+(3+K_p K_{cd})s+\varphi K_p} \quad [1c]$$

The characteristic equation for $H_2(S)$ and $H_3(S)$ both have a similar form with an adjustable "s" coefficients in the denominator while the $H_1(S)$ equation does not have an adjustable coefficient. In $H_2(S)$ and $H_3(S)$ the system damping can be similarly tuned whether velocity is used in either the controller or the feedback. Manipulating the form of the feedback allows us to manipulate the form of the characteristic equation of the overall closed-loop transfer function. Therefore, the derivative feedback allows us to manipulate the damping, and thus the stability, of the system.

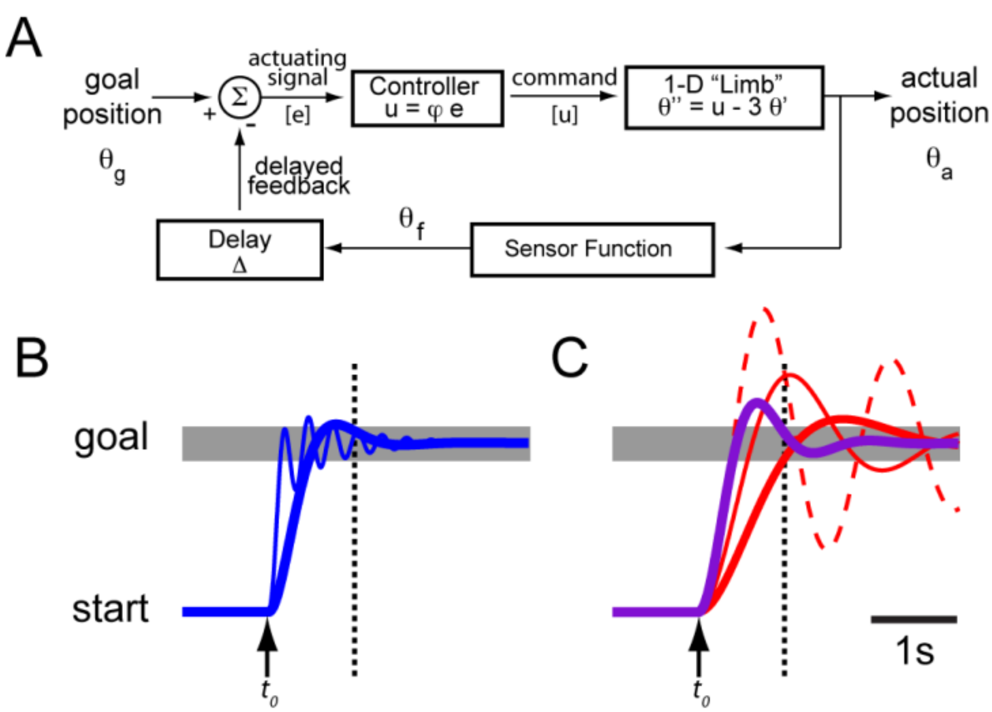

Figure 3.1: Simplified model of closed-loop feedback control for goal-directed reaching. A) Simplified model demonstrating how feedback delay (Δ) and information content (Sensor

Function) impacts performance of a proportional controller regulating the position of a damped inertial "limb". Controller gain φ was varied to test the capabilities of the model system. B) Simulation results when the feedback path emulates proprioception (i.e. Delay Δ = 0.06 s and Sensor Function $\theta_f = \theta_a + 0.15\, d\theta_a/dt$). Arrow indicates the time of change in desired position. Dotted line: t = 1s. Grey band: goal target zone. The limb obtains the goal within the time constraint over a broad range of controller gains with position + velocity feedback (Thick blue trace: φ = 20; Thin trace: φ = 130). C) Simulating visual feedback (Red: Delay Δ = 0.12 s and Sensor Function $\theta_f = \theta_a$; Thick red trace: φ = 5; Thin trace: φ = 10; dashed trace: φ = 20). With position feedback, no value of φ enables success when Δ = 0.12s. Also shown (Purple; φ = 20) is an acceptable solution obtained when simulated visual feedback also includes velocity information: $\theta_a + 0.15\, d\theta_a/dt$.

Consider now a task wherein the limb should acquire and hold a goal target in less than 1 second (Fig 3.1B, vertical dotted line). If feedback emulates the dynamics and delay associated with muscle spindle afferents [i.e., position plus velocity feedback and a sensory delay of ~60 ms; (Cameron et al. 2014)], a wide range of controller gain values (φ, ranging from 20 to 130) can yield acceptable performance (Fig 3.1B, blue traces). Thus, position plus velocity feedback can yield robust performance that is relatively insensitive to controller gain while requiring minimal computational load (i.e., implementing a simple proportional control law). In the absence of reliable proprioceptive feedback (e.g. post-stroke), one might be inclined to substitute visual feedback. The model suggests that relying solely on hand position feedback relative to a fixated target with a visual delay of ~120 ms (Cameron et al. 2014) cannot yield acceptable capture-and-hold performance in this task for any proportional gain value (Fig 3.1C, red traces). Even if the limb reaches the target within 1 second, the hold criteria is subsequently violated. Acceptable performance can be restored only by making the feedback and/or controller more complex (e.g., with position plus velocity feedback encoding; Fig 1C, purple trace).

This study sought to determine how best to synthesize and deliver supplemental kinesthetic feedback and to test its ability to enhance performance of goal-directed stabilization and reaching behaviors in neurotypical adults. In a first set of experiments, we evaluated different weighted combination of moving hand position and velocity information to find the form of supplemental state feedback that minimizes performance error during stabilization and reaching tasks performed with the arm. Based on the predictions of the computer model, we hypothesized that a vibrotactile feedback encoding scheme that includes a modest amount of hand velocity information - but weighted more heavily toward position information - would best impact performance of these behaviors. In a second set of experiments, we compared this optimal limb state feedback to hand position error feedback [the simplest form of “goal aware” feedback (Tzorakoleftherakis et al. 2016)] to determine the performance benefits of each encoding scheme. We hypothesized that both state and error feedback would be capable of enhancing performance of stabilization and reaching behaviors in the absence of visual feedback. We furthermore hypothesized that error encoding would likely yield superior enhancement of these behaviors due to the additional task-relevant information that error feedback contains. Preliminary aspects of this study have been presented in abstract form (Krueger et al. 2016).

3.2 Methods

Twenty-six healthy humans (13 female) were recruited from the University of Genoa community and all provided written informed consent to participate in this study. All procedures were approved by local Institutional Review Boards serving the University of Genoa (ASL3 Genovese) and Marquette University in accord with the 1964 Declaration of Helsinki. None of the participants had known neurological disorders. Participant ages ranged from 22 to 32 (26 ±

3) years. All of the participants self-reported to be right handed. All participants had normal or corrected-to-normal vision and all were naïve to the purposes of the study.

Each participant took part in up to three experimental sessions conducted on separate days. The experiments were designed to determine whether encoding state or error information about a moving limb (e.g., the dominant arm) into a vibrotactile feedback stream applied to a non-moving body part (e.g., the non-dominant arm) would best enhance performance of stabilization and reaching behaviors in the absence of ongoing visual feedback of performance. Specifically, the first session (Experiment 1) sought to determine the best (optimal) combination of limb state information, hand position and velocity feedback, to encode within the vibrotactile feedback applied to the contralateral arm. The purpose of the second and third sessions (Experiment 2) was to compare the effects of encoding optimal state feedback with that of encoding an objective measure of hand position error.

3.2.1 Experimental Setup

Participants were seated comfortably in a high-backed, adjustable-height chair in front of a horizontal planar robotic manipulandum, which has been described in detail previously (see Casadio et al. 2006) (Fig 3.2A). The participant was seated approximately 25 cm from the center of the workspace with the right arm strapped to the robotic handle and its integrated arm support. The seat height was adjusted such that the abduction angle of the right shoulder was between 75° and 85°. The left arm rested comfortably on a horizontal planar armrest situated below that plane of motion of the robot; the forearm and hand pointed forward as in Fig 3.2A. An opaque shield was placed over the workspace to block the participant's view of the moving arm and the robotic apparatus. View of the stationary arm was not precluded. A vertical computer monitor was mounted in direct view, 0.7 m in front of the participant and just above the shield to avoid neck strain; this display provided visual cues of hand and target position and motion when appropriate (the scheduling of visual feedback is described below).

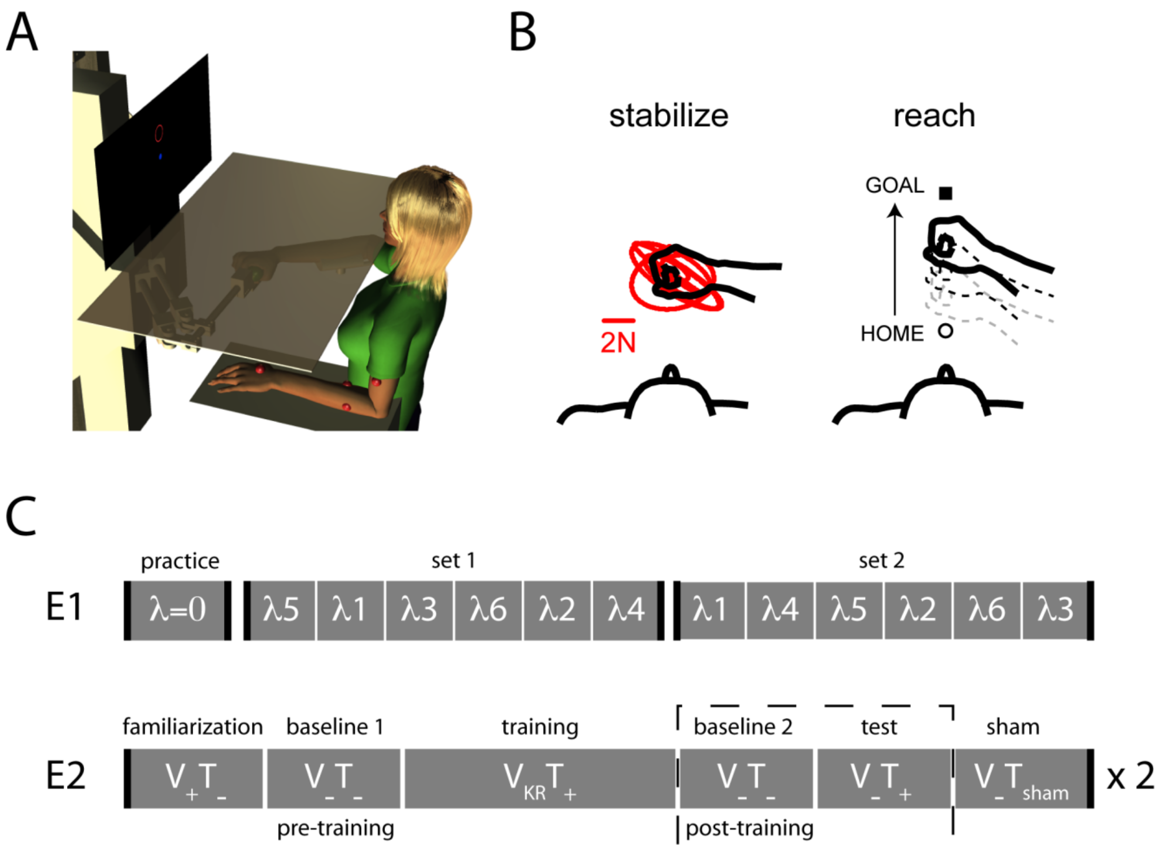

Figure 3.2: Experimental setup and protocol. A) Participant at robot holding the end effector of a planar manipulandum, with visual occlusion shield; the left arm shows the standard placement of the four tactors (red dots). B) Tasks. C) Sequence of events in each experiment. E1: Experiment 1. E2: Experiment 2; baseline 2 and test 2 were counter balanced in order across participants. Visual feedback (V) and vibrotactile feedback (T) was either continuous (+), absent (-), or only used for providing the results at the end of each task (KR). This sequence was used during 2 sessions, in which the only difference was that the vibration feedback encoded either error or state.

Supplemental kinesthetic feedback was provided using a two-channel (4 "tactor") vibrotactile display attached to the non-moving arm. Each tactor consisted of a micro-motor with integrated eccentric rotating mass (Pico Vibe 10 mm vibration motors; Precision

Microdrives Inc., Model # 310-117), with an operational frequency range of 50 to 250 Hz and peak vibrational amplitude of 0.97N, which corresponded to an expected maximal forearm-plus-hand acceleration ranging between 0.53 m/s^2 and 0.77 m/s^2, depending on participant anthropometrics. The tactors were driven by "pulse-step" control whereby commanded increments in tactor activation levels were realized by first activating the tactor fully for a brief moment (0.8 milliseconds) before reducing activation to the commanded level; this control scheme was used to successfully overcome undesirable static friction and to increase repeatability of tactor excitation levels. For all participants, tactors were initially arranged with one tactor on the back of the hand, two tactors on the forearm, and one on the upper arm (Fig 3.2A; default tactor locations indicated by red spheres). In this standard configuration, the hand tactor (+y tactor) was placed approximately one cm proximal to the first and second finger metacarpophalangeal joints. The forearm tactors were placed approximately 3 cm distal to the cubital fossa, one on each side of the forearm (+x tactor on the right, –x tactor on the left). The upper arm tactor (-y tactor) was placed about 5 cm proximal to the cubital fossa, on the bicep muscle belly. Elastic fabric bands were used to secure the tactors.

We then performed a verification procedure wherein we adjusted tactor locations slightly so that each participant could indicate reliably which tactor or pair of tactors was activated at any given time. This was done using low, middle, and high intensity vibrations (approximately 10%, 40% and 90% full scale range, respectively). The adjustment / verification procedure began by asking the participant to place the hand's cursor at each of the four corners of the screen and to tell the experimenter how many and which tactors were vibrating (at ~90% FSR). This was repeated two times, once near the center of the screen (~10% FSR) and again approximately mid-way between the center and the edge of the screen (~40% FSR). Next, the participant was asked to place the hand's cursor at the middle of the screen, and then to move away from and back towards the center so as to feel the changing intensity. If the participant could not give clear and correct indication as to which tactor was active and the appropriate direction of activation change, further personalized tests were used to isolate and resolve the problem. This setup procedure successfully identified well-discriminated stimulation sites in all participants and typically took about 10 minutes to complete. It should be noted however that for 16 of our healthy participants, finding well-discriminated sites required repeated adjustments (see 3.4 DISCUSSION).

The vibrotactile display was calibrated to the robot's workspace such that motions of the robot handle to the right would induce the +X tactor to vibrate, whereas motions of the robot handle away from the participant (i.e., toward the monitor) would induce the +Y tactor to vibrate. The various mappings of hand kinematics onto vibratory stimuli are described in greater detail below.

3.2.2 Experimental Tasks

Across the three days of testing, participants were required to perform two different experimental tasks (Fig 3.2B). This included: i) stabilizing the hand at a fixed point in space against robotic perturbations; and ii) reaching to 16 spatial targets that sampled 16 movement directions and two movement extents.

<u>Stabilizing</u> - When performing the stabilization task, participants attempted to hold the robot's handle steady at a comfortable "home" position located in the center of the workspace. During each 1 minute stabilization trial, the robot generated spatially complex sum-of-sinusoid force perturbations that contained predictable low frequency and unpredictable high frequency components (Equations 2):

$$F_X = 0.75 \cdot \cos(2\pi \cdot 1.75 \cdot t) + 0.75 \cdot \cos(2\pi \cdot 1.2 \cdot t) + 6 \cdot \cos(2\pi \cdot 0.25 \cdot t) \quad [2a]$$

$$F_Y = 0.75 \cdot \sin(2\pi \cdot 1.65 \cdot t) + 0.75 \cdot \sin(2\pi \cdot 1.1 \cdot t) + 6 \cdot \sin(2\pi \cdot 0.25 \cdot t) \quad [2b]$$

During pilot testing, some individuals adopted a strategy whereby they stabilized hand position by stiffening the arm and ignored the vibrotactile feedback altogether. We therefore gave study participants the following instructions: "Without stiffening your arm, keep your hand as steady as possible using the vibration feedback." Depending on the specific experimental test conditions, participants could perform the stabilization task under three different visual feedback conditions. In the first condition (continuous visual feedback; V_+), a 0.5 cm radius cursor was always visible on the computer screen and tracked the motion of the hand continuously. In the second feedback condition (no visual feedback; V_-), participants attempted to stabilize the hand at the home position without ongoing cursor feedback (i.e., the cursor was never visible). In the third visual feedback condition (Knowledge of Results; V_{KR}), participants only received cursor feedback of hand position after the trial was complete. Reminders to avoid stiffening the arm and to focus on the vibration were repeated periodically throughout the stabilization trials.

Reaching - During this task, participants performed out-and-back reaches to 16 targets. For each of the targets, participants reached to the target, paused for a few seconds, and executed a return-to-home movement for a total of 32 discrete goal directed reaches. Each target-capture movement started from the same comfortable "home" position as in the stabilization task. The 16 spatial targets were equally distributed along the perimeter of two concentric circles that were centered on the home position (center target). The inner circle (near targets) was 5 cm from the home position, whereas the outer circle (far targets) was 10 cm from home. We attempted to equalize the Fitts Law difficulty of the different movements by scaling target size such that inner targets had 1 cm radii whereas outer targets had 2 cm radii. The presentation order of targets was pseudorandomized within each block. As in the stabilization task, reaching trials could be conducted with one of the three different forms of visual feedback.

In the V_+ case, a 0.5 cm radius cursor tracked the motion of the hand continuously. At the start of a trial, an 800 Hz audio cue sounded for 0.5 seconds and one of the 16 visual targets was presented on the video display. When the cursor reached the target, the 800 Hz audio cue sounded again and the participant could relax. After a 2 second pause, the current target disappeared, a final 800 Hz audio cue sounded, the home target appeared, and the participant reached back to the starting position in anticipation of the next trial.

In the V_- trials, the cursor was never visible as participants attempted to capture the visual targets. At the start of these trials, the 800 Hz audio cue sounded and one of the 16 visual targets appeared. Upon completing the reach, the participant announced that they thought they had arrived to the target and the experimenter registered that event by pressing a button. At this point, the 800 Hz audio cue indicated the trial was complete regardless of the spatial accuracy of the movement. Following a 2 second pause, the current target disappeared, a final 800 Hz audio cue sounded, the home target appeared, and the participant reached back to the starting position. Once again, the participant verbally indicated completion of the movement and the experimenter registered the event in anticipation of the next trial.

In V_{KR} trials, participants received visual feedback of cursor / hand position only after the reach was complete; they were to use that feedback to correct for any terminal target capture errors. In this condition, the participant reached to the target without visual feedback as in the V_- case. When the participant announced that they had arrived to the target, the experimenter pressed the button and the cursor appeared. If the cursor was correctly on-target, the 800 Hz audio cue sounded. If the cursor was incorrectly off-target, an annoying, descending-pitched audio tone sounded for 1.5 seconds, and the participant was required to correct the error with the aid of visual feedback. Upon arriving on the target the pleasing 800 Hz audio cue sounded. After a 2 second pause, this sequence of events was repeated for the return-to-home reach.

In all three conditions, time constraints were placed on each reach. If the participant had not reached the target or announced to the experimenter they had reached the target within 10 seconds, the experimenter terminated the movement and the experiment proceeded as normal. In all cases, participants were instructed to "Capture the target as quickly and accurately as possible." As a reminder to capture the target quickly, reach targets turned from red to blue 1 second after they appeared.

3.2.3 Vibrotactile feedback encoding schemes

Hand position data derived from the robot's optical encoders were used to generate three distinct forms of vibrotactile cues. The first, *state feedback,* was a weighted combination of hand position and velocity information. Position feedback was calibrated such that the intensity of vibrotactile feedback was zero in all tactors when the hand was centered on the home target and increased proportionally within the vibrotactile display as a vector representation of the hand's deviation from that position. The vibration was 0 only when the cursor was at the center of the home target's location. Vibratory stimulation reached 90% full scale range (FSR) when the hand reached the bounds of the visual display (corresponding to a displacement of 15 cm from home). The bijective mapping between hand position and stimulation within the X-Y vibrotactile display adhered to the intuitive registration between the robotic and vibrotactile reference frames. Velocity feedback was calibrated such that the intensity of vibrotactile feedback was zero in all tactors when the hand was at rest, regardless of where the hand was in the workspace. Vibratory stimulation increased proportionally within the vibrotactile display as a vector representation of the hand's instantaneous velocity. Vibratory stimulation reached 90% FSR when hand speed reached 20cm/s. Prior to use, participants were instructed that the state feedback vibration encoding scheme provided position and velocity feedback information relative to the home position.

The second form of vibrotactile cue, position *error feedback*, was defined as the instantaneous signed error between the hand and target locations. Error feedback was calibrated as for position feedback, except that the origin of the vibrotactile display was always centered on the current target rather than always on the home position. The vibration was set to 0 if the cursor was anywhere within the current specified target. The sign and magnitude of error in each feedback channel (X or Y) determined which tactor within that channel was activated (+ or -) and the extent to which it was activated (stronger vibrations indicated larger errors). Prior to use, participants were instructed that this vibration feedback scheme provided information about the position error between the cursor and the target.

The third form of vibrotactile feedback, *sham feedback*, was created by applying a Fourier transform to a selected vibrotactile feedback signal recorded during pilot testing from a participant performing a dynamic stabilization task while using error feedback. The phase of the selected feedback signal was scrambled in the frequency domain and inverse Fourier transformed, yielding a signal that maintained the power content of the original vibration signal but did not encode any information about either the hand position or the current task. Stabilization about the target produced a signal containing both high- and low- frequency changes in the vibration. By shuffling the signal power in the frequency domain, the resulting sham signal obtained characteristics similar to those of both the reaching and stabilization tasks in both the state and error feedback conditions, with high, low, and off levels of vibration. The resulting sham signal was 1 minute long and was looped during trials lasting longer than 1 minute. The sham signal was only used at the end of an experimental session. Participants who noticed the onset of sham stimulation and voiced their awareness were instructed to nevertheless attempt to use the vibration as best as they could.

3.2.4 Experiment 1 - Optimizing State Feedback

There currently exists no theoretical or empirical guidance on how best to combine information about a moving limb's dynamic state when synthesizing and delivering supplemental kinesthetic feedback for promoting stable and accurate limb control in the absence of visual feedback. The first experiment used several different combinations of hand position and velocity information to systematically compare the utility of both forms of information to promote limb stability and movement accuracy in the absence of ongoing visual feedback.

Fifteen participants (9 female; age range 22 to 32 years) performed 12 matched pairs of one reaching trial (reaches to and from 16 different targets) and one stabilizing trial (1 minute duration). Each pair of trials utilized one of six specific weighted combinations of hand position and velocity information (Equation 3):

$$\gamma(t) = \lambda \cdot \dot{p} + (1-\lambda) \cdot p \qquad [3]$$

where the vibrotactile feedback signal $g(t)$ is a vector function of hand position p and velocity $\dot{p}$. λ is a constant scalar weighting factor such that when $\lambda = 0$ feedback contained only position information, whereas when $\lambda = 1$, feedback contained only hand velocity information.

The λ parameter varied from 0 to 1 in increments of 0.2. Each λ value was tested two times, one time in each of two blocks of 6 matched pairs. The presentation order of λ values was pseudorandomly distributed within each block (an example of one such randomization is depicted in Fig 3.2C, E1). During reaches in Experiment 1, V_{KR} visual feedback was provided only after the movement was complete to allow for terminal correction of target capture errors. Visual feedback was not available during the stabilization (i.e., the V_- condition).

At the start of the experimental session, participants were informed that the vibrotactile feedback could encode several different combinations of hand position and velocity information, ranging from pure position feedback to pure velocity feedback. They were then introduced to the vibrotactile display with position-only feedback (λ = 0.0) and encouraged to freely explore the workspace to develop an understanding of how the vibration feedback interface worked. After free exploration, participants practiced the reaching task and then the stabilization task until they were comfortable with the vibrotactile display and the tasks. Participants were encouraged to use the vibration to complete the tasks to the best of their ability.

Participants then completed the 2 blocks of six matched trial pairs (one λ value per pair). Before assessing performance under each new λ encoding scheme, participants were again encouraged to freely explore the workspace to learn the relationship between vibration and hand position/velocity; they were allowed up to one minute to do so. Participants then completed the reaching trial followed by the stabilization trial. This exploration-reach-stabilize sequence was repeated for each λ value within each block. We designed this sequence of tasks such that the reach and return movements would provide structured practice with the current λ encoding scheme prior to performance testing in the stabilization task. At the end of each matched trial pair, participants were asked to describe, if possible, how they interpreted and used the vibration to perform each task. Although we originally intended the reaching task to serve as structured practice for stabilization, we report performance in both the stabilizing and reaching trials because we observed consistent results in both tasks.

3.2.5 Experiment 2 - Comparison of Optimal State vs. Error Feedback

We next compared effectiveness of two forms of supplemental vibrotactile feedback in guiding performance of stabilization and reaching behaviors in the absence of visual feedback. The first encoding scheme, optimal state feedback, was the best combination of limb position and velocity information identified in Experiment 1. The second scheme, error feedback, involved the encoding of performance error into the vibrotactile information stream. Error encoding is a simple form of "goal aware" feedback (c.f., Tzorakoleftherakis et al. 2016) wherein deviations from a desired position (the "goal") are fed back to the user, who can drive performance back to that desired position. In this experiment, the desired position was defined simply as the instantaneous position of the target.

Fifteen participants (8 Female) participated in 2 experimental sessions at least 2 hours apart (Range 2 hours to 19 days; mean 5±6 days). Both sessions followed the same experimental protocol but used a different type of feedback, *optimal limb state feedback* (as determined by the first experiment) or goal-aware *error feedback*. The presentation order of state and error feedback sessions was counterbalanced across participants.

During each session, participants completed a series of reaching and stabilization tasks guided by various combinations of visual (V) and vibrotactile (T) feedback (Fig 3.2C, E2). First, participants familiarized on the tasks by performing each with continuous vision and without vibration feedback (V_+T_-). Participants repeated the tasks with neither visual nor vibration feedback (V_-T_-) to assess baseline performance before vibration training. Following baseline assessment, participants were introduced to the vibrotactile display and encouraged to freely explore the workspace for up to 3 minutes. Participants then received training throughout the workspace by performing five reaching trials with vibrotactile feedback and visual knowledge of results ($V_{KR}T_+$). Participants concluded training by performing the stabilization task with V_-T_+ feedback. On average, participants took 45 minutes to do this training. We then examined aftereffects of training by having participants complete both tasks without either visual or vibration feedback (V_-T_-) (i.e., post-training baseline testing). We also tested how well participants could use vibrotactile feedback to guide performance of reaching and stabilizing behaviors in the absence of vision by having them perform one trial of each task with only vibrotactile feedback (V_-T_+) (i.e., vibrotactile performance testing). The presentation order of the post-training baseline phase and the vibrotactile performance testing were counter balanced across participants (Fig 3.2C, dashed box). Lastly, the participants performed both tasks with sham vibrotactile feedback (V_-T_{sham}). Participants were provided brief intervals (1 to 2 minutes) of V_+T_- feedback between each experimental phase, thus allowing periodic realignment of visual and proprioceptive maps of space.

At the end of each error or state feedback session, participants were asked to rate the "usefulness" of that particular encoding scheme on a scale that ranged from 1 to 7, by responding to two questions: " How useful was the vibration in the {reaching, stabilization} task?". They were asked to describe, if possible, how they interpreted and used the vibration to perform each task.

3.2.6 Data Analysis

Analysis of participant performance during stabilization and reaching behaviors focused primarily on hand position data, which were derived from the robot described in (Casadio et al. 2006) using Python (Python Software Foundation) and H3D API (SenseGraphics, www.h3dapi.org) running at 60 Hz to collect data from the robot's encoders and control the visual display.

Stabilizing: Conspicuous features of participant performance during stabilization trials included the presence of startup transients at the beginning of each trial and the presence of prolonged hand position "drift" in the absence of ongoing visual feedback (see also Wann and Ibrahim 1992; Scheidt et al. 2005; Suminski et al. 2007). We therefore discarded the first 5 seconds of data in each 60-second trial to eliminate potential start-up transients caused by the onset of force perturbations applied to the hand. We modeled hand position drift along the x and y axes separately as low-order (linear through 3^{rd}-order) polynomial functions of time. The purpose of this manipulation was to isolate variations in the data due to slow drift from moment-by-moment fluctuations caused by the robotic force perturbations of Equation 1. As the 2^{nd}- and 3^{rd}-order models yielded results indistinguishable from the linear model, we only report results obtained with the lowest order model. We then computed the root-mean-square error for the raw position data ($RMSE_{total}$) as well as for the portions of data variance accounted for by the drift model ($RMSE_{drift}$) and by the moment-by-moment fluctuations in the data (i.e., the residuals of the drift model fit, $RMSE_{residual}$). For each component ($RMSE_{total}$, $RMSE_{drift}$, $RMSE_{residual}$), we analyzed only the RMSE values in the second block of trials of six different lambda values performed by each participant. Then, we fit third order polynomials to the variations in $RMSE_{total}$, $RMSE_{drift}$, and $RMSE_{residual}$ values across the population of participants. Finally, we identified the optimal mixture of limb state information within the vibrotactile feedback signal by identifying the lambda value that minimized the third order polynomial fit.

Reaching: Performance in the reaching task was quantified using hand positions sampled when the participant indicated that they thought they had acquired the intended targets. These final reach positions were used to compute two performance measures: *mean absolute error magnitude* (a measure of reach accuracy), and *target capture variability* (a measure of reach precision). Mean absolute error was computed separately for each intended target type {center, near, far} as the average root-mean-square error between the final reach position and the center of the intended target. Target capture variability was estimated separately for each intended target type by computing the area of the 95% confidence interval (CI) ellipse for the entire distribution of final hand positions about the desired target (Johnson and Wichern 1988; Oliveira et al. 1996; see also, Scheidt and Stoeckmann 2007). For the near and far targets, we collapsed across movement directions by counter-rotating the reach endpoints about the home target by the angle of desired target movement. For the center target, we calculated target capture variability in two ways – after counter-rotating by the intended movement direction (as for the near and far targets), and without counter-rotation.

3.2.7 Statistical Analysis

This study tested three main hypotheses via two sets of experiments. The goal of Experiment 1 was to identify the form of vibrotactile limb state feedback (i.e., the specific weighted combination of moving hand position and velocity information) that elicits the best performance of stabilizing and reaching behaviors in the absence of ongoing visual feedback. Based on the predictions of a simple proportional control model, we hypothesized that a vibrotactile feedback encoding scheme that includes a modest amount of hand velocity information - but weighted more heavily toward position information - would best enhance performance of these behaviors. The goal of Experiment 2 was to perform a head-to-head comparison of optimal state feedback and hand position error feedback, which is a simple "goal-aware" encoding scheme (c.f., Tzorakoleftherakis et al. 2016). We hypothesized that both state and error feedback would enhance performance of stabilization and reaching behaviors in the absence of visual feedback. We furthermore hypothesized that error encoding would yield superior enhancement of these behaviors due to the additional task-relevant information contained in this encoding scheme.

Prior to statistical testing, each of the performance measures described above required correction for non-normality (i.e., skew) in their distributions, stemming from the fact that these measures are strictly non-negative. A Box-Cox transformation [$T_\lambda(y) = (y^\lambda - 1)/(\lambda \bar{y}^{\lambda-1})$] (Box and Cox, 1964) was used to correct for distribution skew.

In Experiment 1, we used multivariate analysis of variance (MANOVA), followed by repeated measures ANOVA and Dunnett's multiple comparison t-test (where appropriate) to determine the extent to which stabilization performances ($RMSE_{total}$, $RMSE_{drift}$, and $RMSE_{residual}$) at each λ value varied relative to those at the optimal λ value, which was identified by minimizing the polynomial fit to the population $RMSE_{drift}$ data. For reaching, we similarly analyzed mean absolute error and target capture variability for each target type {center, near, far}. We calculated the within-subject difference between performances at each λ value relative to the performances measured at the optimal λ value identified during stabilization. We then performed a 1-sample t-test to evaluate the statistical significance of the population differences (H_0: difference = 0.0).

In Experiment 2, we tested the ability of vibrotactile feedback to enhance performance of stabilizing. First we quantified the amount of the mean absolute error magnitude accounted for by drift in each of the various training conditions. Then we analyzed the effect of the experimental phase {post-training baseline V_-T_-, test V_-T_+, sham V_-T_{sham}} and feedback type {state, error} on $RMSE_{drift}$ using two-way, repeated measures ANOVA and post-hoc Tukey t-test (where appropriate). For reaching, we analyzed mean absolute error and target capture variability for each target type {center, near, far} by calculating the within-subject differences between performances during the test phase and both the post-training baseline phase and the sham feedback phase. We used paired t-test to compare the V_-T_- and V_-T_+ (no vibration verses vibration) conditions to determine if state and error feedback encoding could improve performance in the absence of vision. We tested V_-T_+ verses V_-T_{sham} to verify that any performance improvement ascribed to state and / or error feedback was due to the specific information content of the vibrotactile feedback rather the mere presence of vibration. Finally, we used paired t-test to compare test phase (V_-T_+) performance across feedback conditions {optimal state, error}, to determine which encoding scheme best enhanced performance during reaching to each target type. All statistical testing was carried out within the Minitab computing environment (Minitab, State College, PA). Bonferroni corrections were applied such that effects were considered statistically significant at the $\alpha = 0.05$ level.

3.3 Results

3.3.1 Experiment 1 - Optimizing State Feedback

Hand position drift was a conspicuous feature of kinematic performance during stabilization in this group of neurologically intact participants (Fig 3.3). As a representative example of this phenomenon, a single trial performed in the absence of visual feedback drifted steadily to the left (Fig 3.3A). Drift was well modeled as a linear function of time for both the X- and Y-axis projections (Fig 3.3B, red dashed lines). In this way, we decomposed raw hand stabilization kinematics ($RMSE_{total}$) into two parts – components characterized by the linear drift model ($RMSE_{drift}$) and residuals of the modeling process ($RMSE_{residual}$), which reflect the participant's ability to compensate for moment-by-moment changes in the imposed robotic forces. We observed hand position drift to some degree in all study participants.

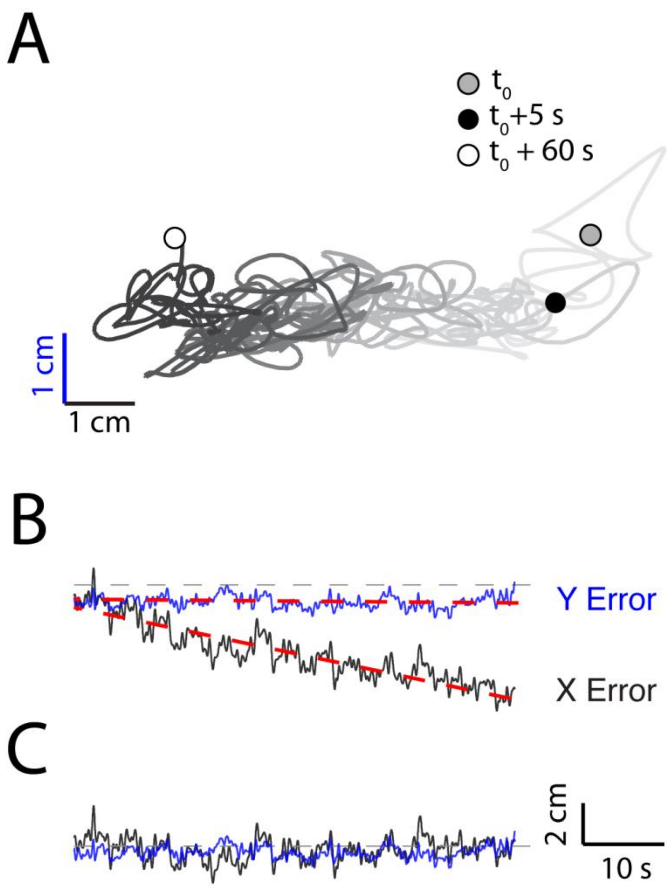

Figure 3: Experiment 1: Selected subject performance in the stabilization task (λ=1.0). A) Cursor trajectory showing drift over time (line shading). Drift was modeled from t=5 seconds to the end of the trial at t=60 seconds. B) Time course of the x (black) and y (blue) components of the endpoint trajectory from t=5 seconds to t=60 seconds. C) Time course of the x (black) and y (blue) components of the endpoint trajectory residuals after removal of the drift, from t=5 seconds to t=60 seconds.

Across the study population, $RMSE_{total}$ varied with the state weighting variable / (Fig 3.4A), with approximately equal contributions of $RMSE_{drift}$ (Fig 3.4B) and $RMSE_{residual}$ (Fig 3.4C) at low / values and an increasing drift contribution at higher / values. We fit a third-order polynomial to the pooled population $RMSE_{TOTAL}$ data and found this relationship to be minimized when / was approximately 0.2. A similar result was obtained upon fitting a third-order polynomial to the pooled $RMSE_{drift}$ data (Fig 3.4B). By contrast, variation across / values in the $RMSE_{residual}$ data appeared to be minimal (Fig 3.4C).

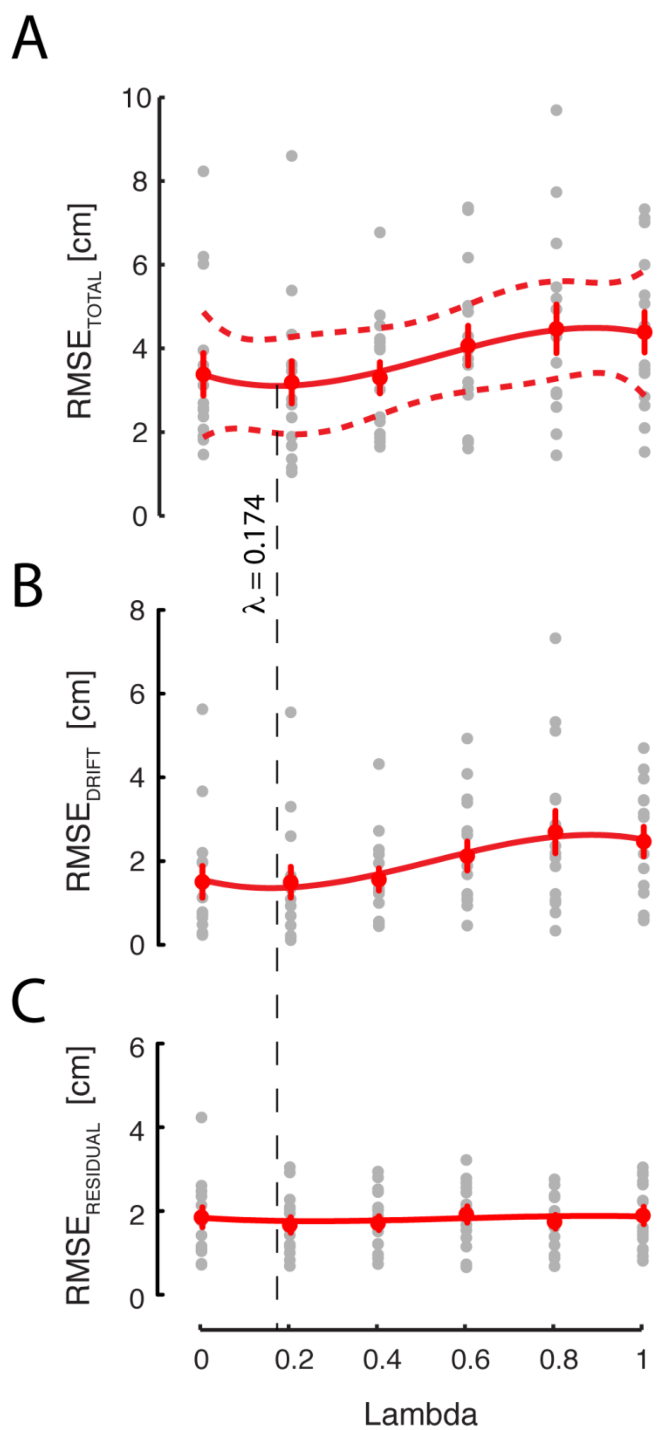

Figure 4: Experiment 1: Population performance in the stabilization task as a function of state mixture parameter lambda, with 3rd order polynomial population fit and 95% function bounds. A) RMSE of the end-effector trajectory. B) RMSE of the drift component of the end-effector trajectory. C) RMSE of the residuals after removal of the drift.

These observations were confirmed using repeated measures MANOVA to compare stabilization performance {$RMSE_{total}$, $RMSE_{drift}$, $RMSE_{residual}$} across / values. MANOVA found significant variation across / values [Wilk's $F_{(15,188)} = 2.536$; $p = 0.002$]. Post-hoc ANOVA found significant variation in $RMSE_{total}$ values [$F_{(5,70)} = 6.02$, $p < 0.0005$] such that Dunnett multiple comparison tests (referenced to control level: / = 0.2) revealed significant increases in $RMSE_{total}$ when / = 0.6 ($p = 0.022$), / = 0.8 ($p = 0.001$) and / = 1.0 ($p = 0.001$). Similarly, post-hoc ANOVA [$F_{(5,70)} = 5.52$, $p < 0.0005$] and Dunnett multiple comparison tests found significant increases in $RMSE_{drift}$ between the control level / = 0.2 and both 0.8 ($p = 0.002$) and 1.0 ($p = 0.005$). By contrast, post-hoc ANOVA found no significant variation in $RMSE_{residual}$ across / values [$F_{(5,70)} = 1.22$, $p = 0.311$].

Kinematic performance of reaching movements also varied with /, even though exposure to each new / encoding scheme was very brief prior to structured reach training. This was most clearly evident in the measure of target capture variability obtained using final hand positions recorded during return-to-home movements. Figure 3.5 depicts all final hand positions achieved by one participant while reaching in the absence of ongoing visual feedback but in the presence of / - weighted vibrotactile feedback. The yellow ellipses represent 95% CIs on the total distributions of return-to-home movement endpoints recorded under each / feedback condition. The precision of return-to-home reaches degrades substantially with increasing / values. / -dependent variations in performance were more difficult to discern for reaches directed to the near and far targets.

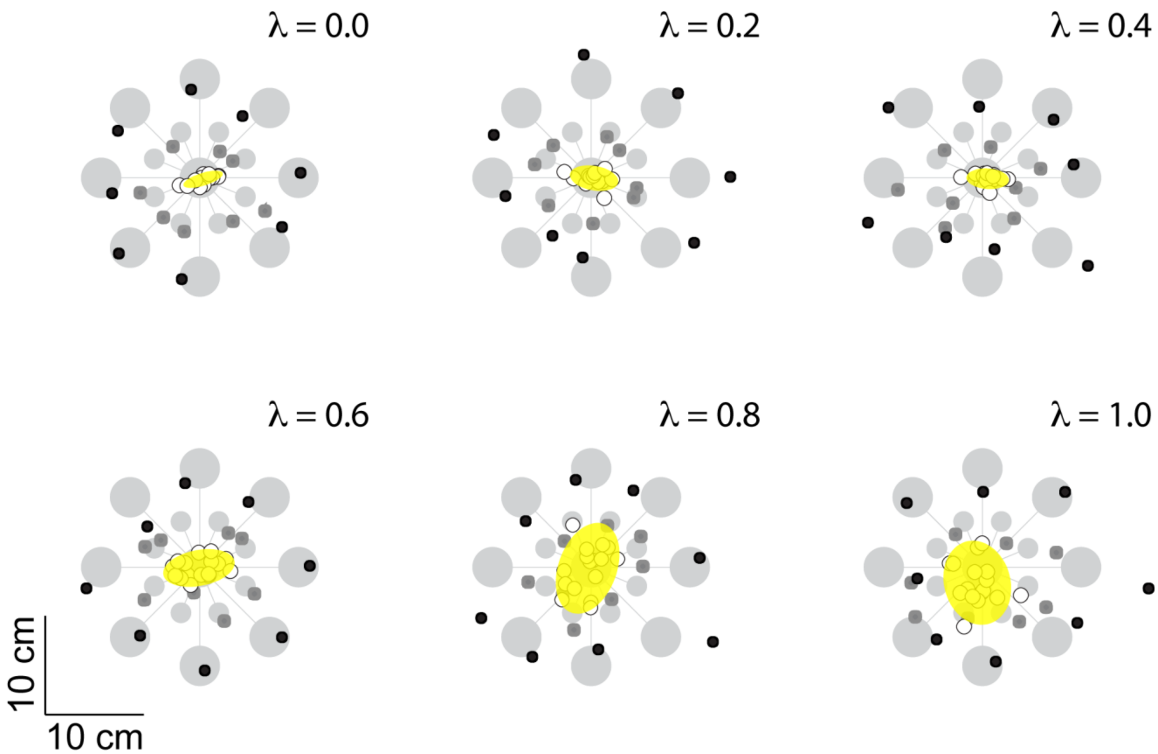

Figure 5: Experiment 1: Selected subject performance in the reaching task for each λ value in V_{KR} visual condition. Yellow ellipses represent the two-dimensional 95% confidence intervals of the return-to-home reach endpoints.

Across the study population, target capture variability for return-to-home reaches exhibited significant variation across / values [ANOVA: $F_{(5,70)} = 6.01$, $p < 0.0005$] such that Dunnett multiple comparison tests revealed significant increases in target capture variability when / = 0.6 (p = 0.034), / = 0.8 (p = 0.028) and / = 1.0 (p = 0.006) when compared to / = 0.2 (Fig 3.6A). This outcome suggests that low / values enhance spatial localization of the hand about the central reference location.

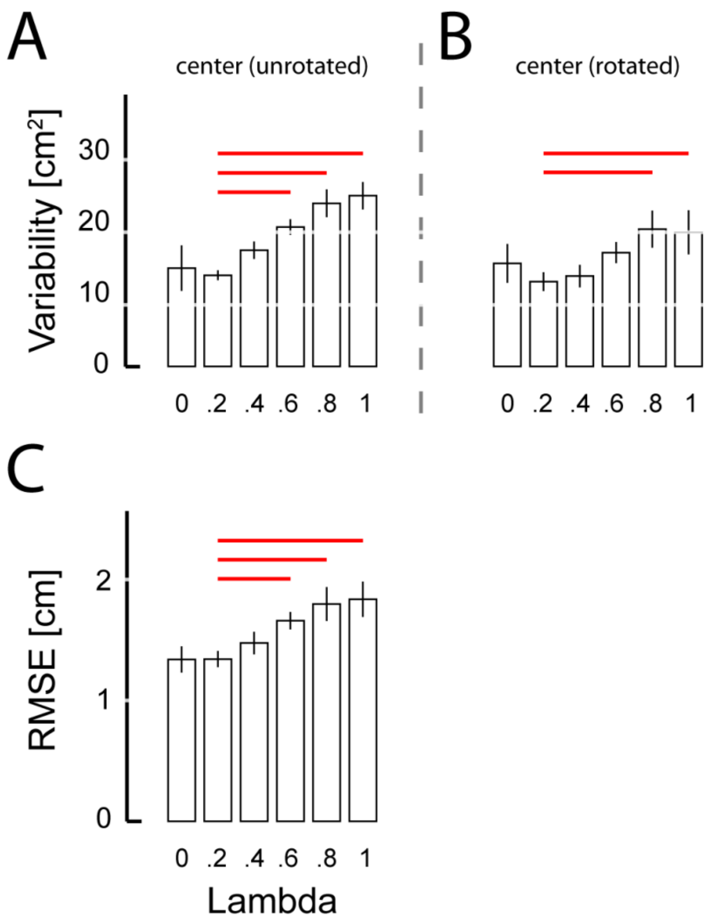

Figure 6: Experiment 1: Population statistics for reaching task, as a function of state mixture parameter lambda. Error bars represent ± 1 SEM. A) Variability of raw reach endpoints about the home target (area of an ellipse fit to the reach endpoints). B) Variability of reach endpoints at the central target location after collapsing across movement directions. C) Mean absolute error (RMSE) at the central target. Red lines: $p < 0.05$.

We also computed target capture variability and mean absolute error at the center, near and far targets after collapsing across movement directions (i.e., after counter-rotating reach endpoints by the intended movement direction about the home target). MANOVA found significant variation across / values within the six datasets (2 performance measures x 3 target sets) [Wilk's $F_{(35,271)} = 1.986$; $p = 0.001$]. Post-hoc ANOVA found a significant main effect of / for both performance measures at the center target [$F_{(5,70)} > 3.60$, $p < 0.006$ in each case] (Figs 3.6B, 3.6C), but no main effect of / for either measure at the near and far target sets [$F_{(5,70)} < 1.31$, p

> 0.270 in all cases] (data not shown). At the center target, Dunnett multiple comparison tests revealed significant increases in target capture variability when / = 0.8 (p = 0.011) and / = 1.0 (p = 0.018) compared to when / = 0.2 (Fig 3.6B). Dunnett multiple comparison tests also revealed significant increases in mean absolute error magnitude when / = 0.6 (p = 0.025), / = 0.8 (p < 0.001) and / = 1.0 (p < 0.001) compared to when / = 0.2 (Fig 3.6C).

3.3.2 Experiment 2 - Comparison of Optimal State vs. Error Feedback

Figure 3.7 contrasts one participant's stabilization performance during Experiment 2 sessions wherein state feedback (top) and error feedback (bottom) was administered. During task familiarization trials with ongoing visual feedback but no tactor feedback (V_+T_-), the participant readily maintained hand position centered on the home target with virtually no drift. During baseline testing, when visual feedback was subsequently removed and the vibration was not yet introduced (V_-T_-), hand position gradually deviated from the home target, albeit in different directions on different trials. After performing about 45 minutes of training with vibrotactile feedback during reaching and stabilizing, the participant persisted in exhibiting drift during post-training baseline assessment (although drift magnitude appears to have decreased somewhat after training). By contrast, the participant successfully eliminated drift when provided vibrotactile feedback of either state or error feedback (V_-T_+). This effect was due to the information contained within the feedback and not the mere presence of vibrotactile stimulation, because the magnitude of drift was at least as great during sham stimulation trials (V_-T_{SHAM}) as it was during the baseline trials.

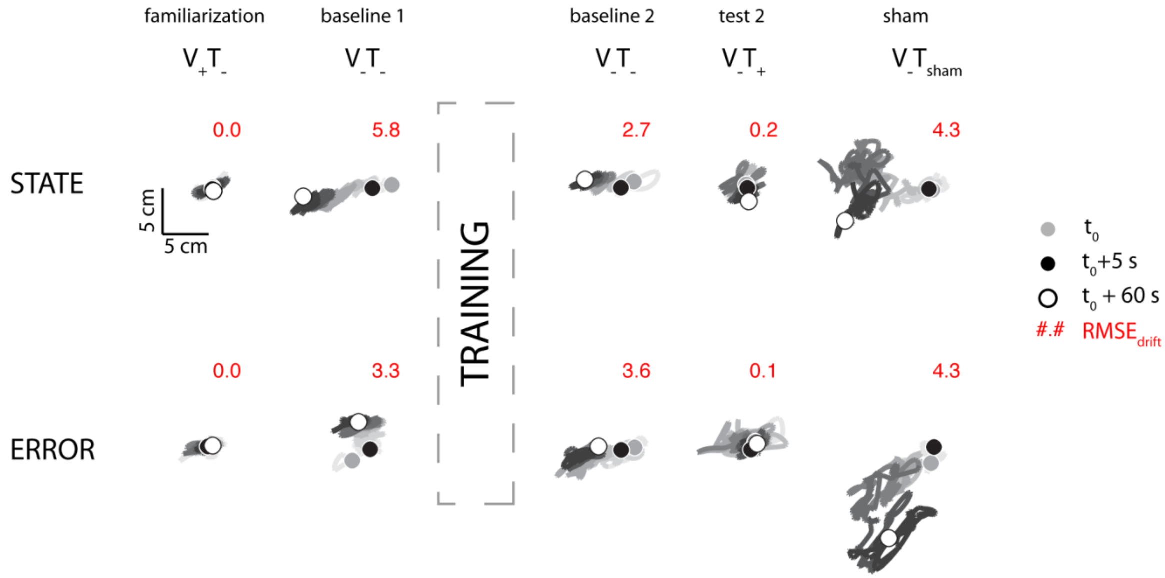

Figure 7: Experiment 2: Selected subject performance in the stabilization task. Cursor trajectory showing drift over time (line shading) varies with the presence and type of vibration feedback. Drift was modeled from t=5 seconds to the end of the trial at t=60 seconds. Values in red are the $RMSE_{Drift}$ for that trial.

Based on these observations, we focused our analysis of population behavior on $RMSE_{drift}$ during the post-training baseline (V_-T_-) testing (V_-T_+) and sham feedback (V_-T_{SHAM}) phases of this Experiment (Fig 3.2C). Two-way repeated measures ANOVA found that when stabilizing about the home target, $RMSE_{drift}$ varied dramatically across experimental phases [$F_{(2,70)} = 23.76$, $p < 0.0005$] but importantly not across feedback conditions [$F_{(1,70)} = 0.56$, $p = 0.457$], with no interaction between these two factors [$F_{(2,70)} = 2.74$, $p = 0.071$] (Fig 3.8). Dunnett multiple comparison tests on the effect of experimental phase (control level: V_-T_+ test phase) revealed that the significant main effect was the result of a decrease in $RMSE_{drift}$ during the V_-T_+ test phase as compared to both the V_-T_- post-training baseline phase ($p < 0.0005$) and the sham stimulation phase (V_-T_{SHAM}: $p < 0.0005$). The difference between the post-training baseline and test phases was not the result of an order effect (i.e., additional practice on the tasks) because the presentation order of these two phases was counter balanced across participants. Moreover, the benefits of vibrotactile feedback were specific to the correction of $RMSE_{drift}$, as separate ANOVA and Dunnetts tests revealed no systematic benefit of test phase vs. post-training baseline performance on $RMSE_{residual}$ values for either feedback type ($p > 0.211$ in both cases).

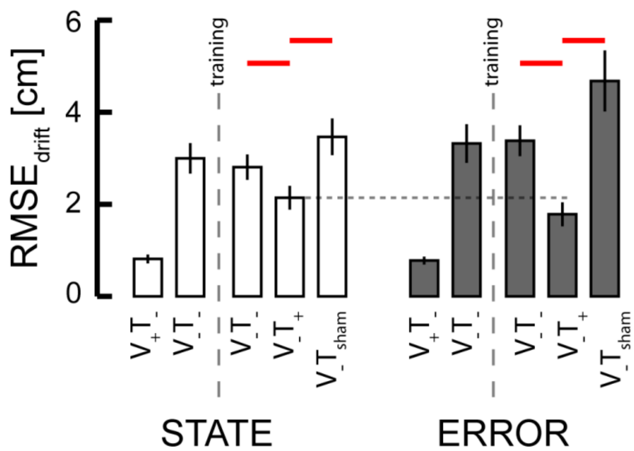

Figure 8: Experiment 2: Population statistics in the stabilization task for error and state feedback. Red lines: $p < 0.05$.

The absence of a significant main effect of vibrotactile feedback type on $RMSE_{drift}$ during stabilization was not entirely unexpected because, in the neighborhood of the home target, the information content of state and error encoding schemes is really quite similar, deviating by the small amount of velocity information contained within the state feedback. By contrast, the two encoding schemes differ markedly in the neighborhood of targets that are not centered upon the origin of the workspace, defined in this study as the center of the home target. Figure 3.9 depicts all final hand positions achieved by one participant while reaching in the Experiment 2 sessions wherein state feedback (top) and error feedback (bottom) was administered. During task familiarization trials with ongoing visual feedback but no tactor feedback (V_+T_-), the participant captured the center, near and far targets with accuracy and precision. When visual feedback was subsequently removed during pre-training baseline testing ($V_{-}T_{-}$), target capture performance collapsed in the sense that reach endpoints deviated wildly from all the intended targets. Reaches to the near and far targets systematically overshot their intended targets whereas the dispersion of return-to-home reaches increased greatly. After performing about 45 minutes of training with vibrotactile feedback during reaching and stabilizing behaviors, the participant appeared to exhibit beneficial aftereffects of training during the post-training baseline assessment without vibration in the sense that final return-to-home hand positions appeared to cluster more tightly around the center target. Aftereffects of training in this second baseline phase were more difficult to discern at the near and far targets. By contrast, beneficial effects of concurrent vibrotactile feedback were evident and specific to the different encoding schemes during the test phase performed without cursor feedback ($V_{-}T_{+}$) (Fig 3.9; red dashed box). Although target capture accuracy and precision appeared to improve substantially with concurrent state feedback at all three target sets {center, near, far}, target capture performance with error feedback was undoubtedly superior for reaches to the near and far targets. This striking difference between post-training baseline and test performance was not merely an order-effect, as the presentation order of these two blocks was counter-balanced across participants. As with stabilization, this beneficial effect of vibrotactile feedback was due to the information contained within the feedback and not the mere presence of vibrotactile stimulation, because the improvements in reach accuracy and precision were eliminated upon switching to sham stimulation ($V_{-}T_{SHAM}$).

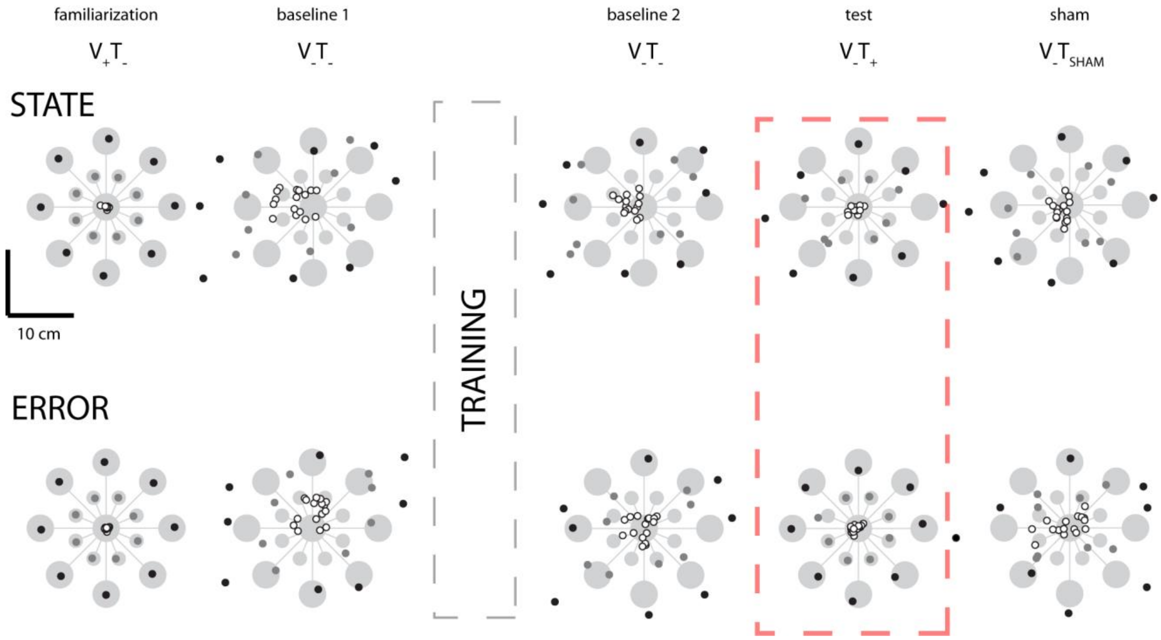

Figure 9: Experiment 2: Selected subject performance in the reaching task Compare performances in the test phases (red dashed box) to the baseline 2 and sham phases.

We used two-way repeated measures ANOVA to test the ability of optimal state and error feedback schemes to enhance performance of goal-directed return reaches toward the (unrotated) center target (Figure 3.10; red significance bars). We found that reach endpoint variability varied systematically across experimental phases [$F_{(2,70)} = 42.87$, $p < 0.0005$], but not systematically across feedback conditions [$F_{(1,70)} = 0.05$, $p = 0.823$]. Within both feedback sessions, Dunnett multiple comparison tests revealed that un-rotated center target capture variability in the test block was less than that in the post-training baseline phase ($p < 0.0005$) and in the sham feedback phase ($p < 0.0005$). When we performed the planned comparison of test phase performances across the two feedback encoding schemes (i.e., across experimental sessions), we found that error feedback was better than optimal state feedback in enhancing the precision of return-to-home movements (paired t-test: $T_{13} = 3.93$, $p = 0.002$), with the average ellipse area under state feedback equal to 9.73 cm^2 and the average ellipse area under error feedback equaling 4.74 cm^2, with the average within-subject difference equal to 4.99 ± 6.03 cm^2.

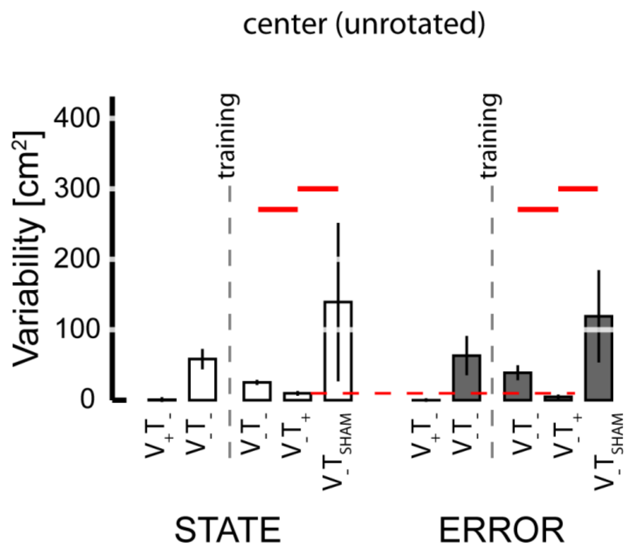

Figure 10: Experiment 2: Population statistics for reaching to the (unrotated) center target. Error bars represent ± 1 SEM. Red lines: $p < 0.05$. Blue lines: secondary analysis with $p < 0.05$.

Similar outcomes to those presented in Figure 3.10 were obtained upon analyzing reaches to all target sets after collapsing across movement directions (Fig 3.11; red significance bars). Within both performance measures {reach endpoint variability, mean absolute error magnitude}, MANOVA found significant effects of experimental phase {post-training baseline, test, sham} [Wilk's $F_{(4,494)} = 68.841$; $p < 0.0005$], feedback condition {optimal state, error} [Wilk's $F_{(2,247)} = 5.107$; $p = 0.007$], and target set {center, near, far} [Wilk's $F_{(4,494)} = 77.362$; $p < 0.0005$], as well as a strong interaction between feedback type and experimental phase [Wilk's $F_{(4,494)} = 13.560$; $p < 0.0005$]. We therefore performed post-hoc ANOVA and follow-on Dunnett's multiple comparisons tests to explore this interaction for each of the six combinations of two performance measures {target capture variability, target capture error} and three target sets (Fig 3.11).

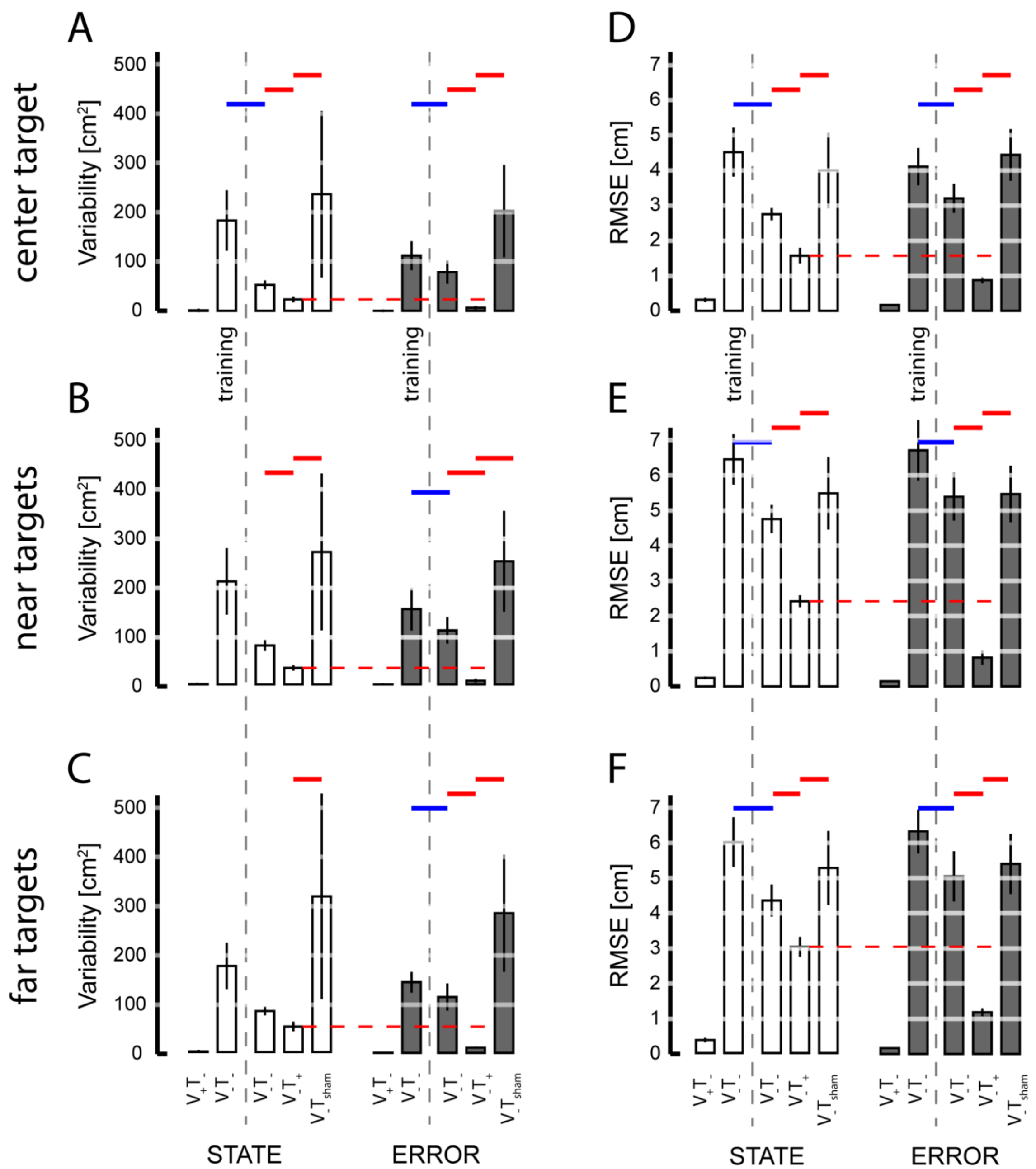

Figure 11: Experiment 2: Population results for reaching task. Error bars represent ± 1 SEM. A-C) Variability of reach endpoints for the three target sets after collapsing across movement directions. D-F) Mean absolute error relative to the center of the target. Red lines: $p < 0.05$.

In contrast to the pattern of performance enhancements observed in Experiment 1, where exposure to each form of vibrotactile feedback encoding was very limited prior to reaching, participants in Experiment 2 demonstrated the ability to use both forms of feedback to enhance target capture accuracy and precision at all three target sets after approximately 45 minutes of training. Within the state feedback session, ANOVA found target capture variability to vary significantly across experimental phases at all three target sets [$F_{(2,44)} > 8.07$, $p < 0.002$ in each case]. Variability was less in the test block than in the post-training baseline block for nearly all participants at all three target types, yielding significant and meaningful benefits of vibrotactile feedback at the center ($p = 0.004$) and near targets ($p = 0.016$) (Fig 3.11; panels A and B; open bars), with a somewhat more modest trend at the far target ($p= 0.068$) (Fig 3.11C; open bars). The benefits of error feedback at all three target types were also very strong [$F_{(2,44)} > 43.70$, $p < 0.0005$ in each case] (Fig 3.11 A-C; filled bars). Post-hoc Dunnett tests found that with error feedback, target capture variability in the test block was less than that in post-training baseline for all target sets ($p < 0.0005$ in each case). The effects for both feedback conditions were specific to the information content embedded within the vibrotactile stimuli because target capture variability in the test phase was less than that in the sham phase for all three target sets under both feedback conditions ($p < 0.004$ in each case). A planned comparison of test phase performance across the two feedback conditions found that error feedback yielded superior reduction in target capture variability at all three targets (paired t-test: $T_{13} > 4.48$, $p < 0.001$ in all three cases).

A similar pattern of results was obtained when we analyzed target capture error within and across feedback sessions (Fig 3.11: panels D-F). Comparing within feedback sessions, ANOVA and post-hoc Dunnett tests identified significant reduction in target capture error when informative vibrotactile feedback was provided for each of the three target sets relative to post-training baseline performance ($p < 0.019$ in all six cases). Performance enhancement was specific to the information contained within the vibrotactile feedback because target capture errors during sham vibration far exceeded those during the test phase for all three target sets under both feedback conditions ($p < 0.001$ in each case). A planned comparison of test phase performance across the two feedback conditions found that error feedback yielded superior reduction (vs. state feedback) in target capture error for all three target sets (paired t-test: $T_{13} > 4.46$, $p < 0.001$ in all three cases.).

Although not a main focus of our study, a comparison of target capture performances before and after vibrotactile feedback training provided evidence for a persistent, beneficial effect of vibration training on subsequent reaching movements performed in the absence of both visual and vibrotactile feedback (Fig 3.11; blue significance bars). MANOVA found a significant main effects of training [Wilk's $F_{(2,160)} = 9.256$; $p < 0.0005$] and target [Wilk's $F_{(4,320)} = 340.761$; $p < 0.0005$] on V_-T_- reaching, regardless of feedback condition [Wilk's $F_{(2,160)} = 0.080$; $p = 0.923$]. Post-hoc ANOVA and Dunnett multiple comparisons tests found strong improvement in reach performance after training with both optimal state ($p < 0.05$ in four of the six cases depicted in Fig 3.11) and error feedback ($p < 0.05$ in all 6 cases).

Finally, survey results suggest that participant preferences were task specific (Fig 3.12). During reaching, participants perceived error feedback to be more useful than optimal state feedback (paired t-test: $T_{13} = 3.42$, $p = 0.004$). During stabilization, participants tended to perceive optimal state feedback to be more useful than error feedback, although the statistical significance of this difference did not survive correction for multiple comparisons.

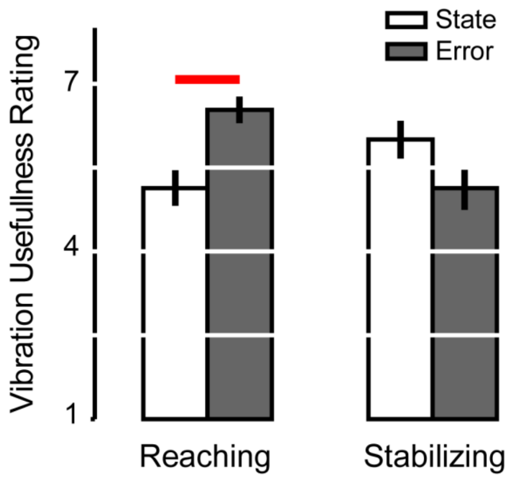

Figure 12: Experiment 2: Assessment of usefulness on a 1-7 scale for state and error feedback for three tasks. Error bars represent ± 1 SEM. Red lines: $p < 0.05$.

Taken together, the results of this study demonstrate that supplementary vibrotactile feedback can yield both immediate performance enhancements during goal-directed stabilization and reaching actions as well as beneficial aftereffects of training that persist after vibrotactile feedback has been removed.

3.4 Discussion

The ultimate objective of this line of research is to develop sensory substitution technologies that enhance closed-loop control of goal-directed behaviors in people with impaired somatosensation. As a first step, we sought here to establish the objective and subjective utility of two forms of supplemental vibrotactile feedback – encoding of limb state or hand position error - for enhancing real-time control of arm stabilization and reaching behaviors in unimpaired individuals. To mimic practical constraints experienced by stroke survivors, many of whom have lost or impaired somatosensation in their more involved arm, we applied the feedback to a body part not directly involved in the action (i.e., the opposite arm). This approach is reasonable as a first step because neurologically normal people frequently exhibit drift in their internal representation of hand position during localization (Jeannerod 1989; Wann and Ibrahim 1992) and stabilization behaviors (Suminski et al. 2007) in the absence of ongoing visual feedback of hand position. Here, in a series of two experiments, we demonstrate that both vibrotactile encoding schemes can effectively eliminate drift when participants stabilize the hand at the origin of the feedback encoding space (i.e., the "home target" for both schemes), even when prior exposure to each particular encoding was limited to just 1 minute. Both encoding schemes similarly and immediately promoted accuracy and precision of reaching movements directed toward the origin of the encoding space. However, the two forms of feedback differed in their ability to immediately enhance reach accuracy and precision at other locations in the arm's workspace. Whereas 1 minute of training did not suffice to allow participants to use any of the tested forms of state feedback to successfully reach to the near and far target sets in Experiment 1, the best of these state feedback encoding schemes (80% hand position information + 20% hand velocity information) and error feedback both improved reach accuracy and precision at spatial targets throughout the arm's reachable workspace after ~45 minutes of training in Experiment 2. The beneficial effects of state and error feedback were specific to the information content encoded within the vibrotactile stimuli because non-informative sham stimulation failed to elicit any meaningful enhancement of performance in any case. This outcome is important for efforts to develop sensory substitution technologies for neurorehabilitation because it demonstrates that people can learn to use easy-to-implement state feedback to improve performance of goal-directed stabilization and reaching behaviors in the absence of ongoing visual feedback. Nevertheless, for reaching, error feedback was superior to optimal state feedback not only on objective measures of target capture accuracy and precision, but also on a subjective measure of perceived utility.

3.4.1 Importance of information content within supplemental vibrotactile feedback

The model simulations described in Figure 3.1 suggest that the control of systems dominated by second-order dynamics with delayed feedback can be enhanced by providing state feedback that adds a modest amount of velocity information to position information (e.g., in a ratio around 20%:80%). The reason for this is that velocity feedback is predictive of position feedback in the sense that the phase of velocity information at any given frequency leads position information by 90° and may therefore enhance perception of changes in limb state. Experiment 1 was designed to test the model predictions. Although we observed evidence for a minimization of hand position drift during stabilization and optimization of reach accuracy and precision at the center target when vibrotactile feedback was comprised of a 20%:80% mix of velocity and position feedback, we did not observe significant variations in the ability of participants to reject the moment-by-moment fluctuations in robotic force perturbations when we systematically varied the relative composition of state feedback. We suspect this negative outcome was due to the limited amount of training with each different combination of state feedback in the first experiment. Indeed, a comparison of reach performance at the near and far targets across both Experiments suggests that the cohort of individuals tested here required up to 45 minutes of training with the optimal state encoding scheme to begin learning how to use that form of feedback. Because training-dependent performance enhancements were limited to drift reduction and the targeting of point-to-point reaches (i.e., we observed no significant improvement in $RMSE_{residual}$), it is likely that full integration of supplemental kinesthetic feedback into the moment-by-moment control of the arm (e.g., during stabilization) requires considerably more training than the mere moments (Experiment 1) or minutes (Experiment 2) provided in the current study. It is also possible that integration of supplemental feedback into moment by moment control would require task-specific training focused on the stabilization task (rather than on reaching as in the current study).

The subjective feedback provided by participants after experiencing each form of state feedback in Experiment 1 was enlightening. During pilot testing, we observed that many participants attempted to solve the stabilization task by stiffening the arm rather than by using the vibrotactile feedback as we had intended them to do. We therefore developed task instructions (and repeatedly reminded the participants) to avoid stiffening the arm and to use the vibration to accomplish each task. In response to investigator queries about the utility of each mixture of state feedback during the survey period after each trial, participants reported that they did in fact use the vibration as instructed in most cases. However, when the vibration contained more velocity information than position information, some participants reported that they had to temporarily stiffen their arm in order to discern the position information within the vibration signal so that they could then make effective use of it. Thus, depending on the value of / , different state feedback encodings yielded strikingly different subjective experiences that could elicit different strategies for integrating the supplemental feedback into real-time control of the arm.

Qualitative differences in the nature of state and error feedback encodings can help explain performance differences in reach to the near and far targets in Experiment 2. Because we defined the origin of the arm's workspace to be at the center of the home target, error and state feedback encodings are similar when the target is at the center of the workspace and / is small (e.g., 0.2) but statistically independent when / = 1.0. However, the origin of the error encoding scheme jumps to the current goal location, wherever it happens to be within the workspace. Thus, when the target jumps to a far target, the origin of error encoding jumps to that location, whereas the origin of state encoding never changes. Thus, when driven by error feedback, test phase target capture performance at the near and far targets in Figure 3.9 closely replicated performance at the home target in that same test phase, and resembled performance at all targets driven by visual feedback in the familiarization phase. But whereas test phase performance driven by optimal state feedback was far better than the baseline and sham phases, target capture variability and RMS error at all target sets was about twice as great with optimal state encoding compared to that observed with error encoding.

The qualitative differences between state and error feedback encoding are also important from the perspective of implementing a practical, supplemental feedback delivery system. Whereas it is easy to implement an error encoding scheme during highly constrained, lab-based stabilization and reaching tasks that utilize a robotic manipulandum to measure instantaneous hand position relative to well-defined spatial targets, it will be much more difficult to define error feedback using wearable technology that must predict the intent and movement goals of the user on a moment-by-moment basis in a unstructured, real-world environment. Although we are not currently aware of technology that is competent to perform intent and goal prediction in uncertain environments, low-cost wearable technologies currently integrate MEMS accelerometers, gyroscopes and magnetometers and can be used to estimate limb state. We do not, however, believe intent and goal prediction to be insurmountable hurdles, as real-time computing systems already are capable of providing goal-aware feedback encodings that enhance human performance of difficult but well-defined tasks such as balancing an inverted pendulum while minimizing both kinematic error and control effort (Tzorakoleftherakis et al. 2016).

3.4.2 Exposure to vibrotactile feedback of limb state induces spatial learning

The tasks participants performed in the current experiments required them to learn how hand position in the horizontal plane mapped onto target location within the vertical plane of the display screen. More specifically, when participants reached to visual targets, they needed to learn an inverse kinematic map specifying how a desired change in visual cursor position should map onto an appropriate, desired change in hand position. By requiring participants to perform the experimental tasks using vibrotactile cues, we required them to learn at least two features of an additional, interposed transformation: 1) how hand motions influence activity within the vibrotactile display; and 2) whether and how changes in visual target location modulate the patterns of activity within the vibrotactile display. Experiment 1 probed the first of these questions and provided evidence that a state encoding with $/$ = 0.2 enhanced stabilization and return-to-home reaches better than several other state encoding schemes tested. Experiment 2 probed the second question and provided evidence that within the time frame of a single experimental session, error feedback out-performed optimal state feedback in facilitating reaching, particularly to the near and far targets.

Importantly, two experimental observations provide evidence that state feedback did encourage participants to learn this additional spatial map, thus providing a sound rationale for further development of state feedback-based supplemental feedback systems. First, after ~45 minutes of practice with optimal state feedback, we observed performance improvements at the near and far targets during test phase reaching with vibrotactile feedback. Because the order of V_-T_+ test and V_-T_- baseline phases after training was counter-balanced across subjects, we can reject the possibility that this learning effect was due to more prolonged practice on the reaching task in the V-T+ condition. We conclude therefore that participants used the optimal state feedback to improve accuracy and precision of their reaches. Because the near and far targets mapped onto non-zero activation patterns in the vibrotactile display, the observed performance enhancements were not confounded by enhancements that might be due to any similarity with error encoding (e.g., that which exists at the center target). Second, we observed less overshoot in post-training baseline reaches performed without ongoing vibrotactile stimulation (relative to pre-training baseline), especially at the near targets. This observation suggested that prolonged training with optimal state vibrotactile feedback facilitated learning of an internal representation or map of space that was subsequently recalled during post-training baseline testing to guide reaches to visual targets. Because we saw evidence of this second aspect of spatial learning at all three target sets with state feedback, especially with regards to target capture error (RMSE) (Fig 3.11, blue significance bars), it is possible that optimal state feedback can be as effective as error feedback at encouraging participants to learn the spatial relationships between target location, hand position and vibrotactile stimulation. Future studies should be designed and conducted specifically to explore how participants learn to use supplemental vibrotactile feedback to shape internal representations of body configuration.

3.4.3 Potential applications of supplemental vibrotactile stimulation

Wearable technologies designed to augment human motor performance by providing supplemental vibrotactile stimulation have many potential applications. In perhaps its simplest form, stochastic resonance (c.f., Wiesenfeld and Moss 1995), vibrotactile stimulation can enhance behaviors such as standing balance (Priplata et al. 2003) and grip force production (Enders et al. 2013) via application of subsensory, random, vibrotactile signals onto the soles of the feet or onto the tendon of finger flexor muscles. Stochastic resonance is a nonlinear, cooperative effect in which a weak stimulus of interest (e.g., forces applied to cutaneous mechanoreceptors) entrains large-scale environmental fluctuations (e.g., the injected noise), with the result that the sensitivity of a nonlinear threshold stimulus detector (e.g., cutaneous mechanoreceptor) is greatly enhanced (Wiesenfeld and Moss 1995). In our study, the beneficial effects of vibrotactile stimulation are not the result of stochastic resonance because performance improvements dissipated in the presence of sham stimulation.

A recent set of experimental studies has found that artificial activation of sensory afferents of distal arm musculature (i.e. at the wrist) can improve control of reaching, stabilizing and tracking behaviors performed with the proximal arm (i.e., shoulder and elbow) by adding excitatory drive to central and peripheral sensorimotor control structures (Conrad et al. 2015; Conrad et al. 2011a; b). For example, Conrad and colleagues (Conrad et al. 2011b) applied unmodulated, 70 Hz wrist tendon vibration on the paretic arm of 10 stroke survivors as they made planar, center-out arm movements. Relative to performances measured before the onset of vibrotactile stimulation, three aspects of performance were enhanced during stimulation and for a brief period after stimulation had ceased: hand position stability at the end of reach improved; muscle activity throughout the arm decreased, and grip pressure during movement decreased. As discussed in (Conrad et al. 2011a), possible mechanisms behind improved proximal arm control in response to distal wrist tendon vibration may include improved central (i.e., cortical) sensorimotor integration within spared neural circuits already mediating control of the hemiparetic arm or improved cortical modulation of spinal reflex activity, which acts to elevate spinal reflex thresholds (thereby reducing spastic hypertonia). The beneficial effects of vibrotactile stimulation in our study do not share a common mechanism of action with the effects studied by Conrad and colleagues. Whereas Conrad and colleagues provided vibrotactile feedback that did not itself encode any meaningful information, the effects of our vibrotactile stimulation were specific to the type of information encoded within the tactile data stream.

Many research teams have proposed using vibrotactile displays to inject useful information into the human nervous system. Several recent application include the use of tactile navigation displays for aircraft pilots seeking to fly toward a target (Van Erp 2005), to hover a helicopter (Raj et al. 2000), to provide mission critical information such as which direction is down during conditions of low visibility (Sklar and Sarter 1999), and to enable vibrotactile transmission of spoken language (Novich and Eagleman 2015). By injecting informative vibrotactile feedback to the non-moving arm in our study, we are recruiting alternate sensorimotor control pathways into the task of controlling the moving arm. The results of the present study show that doing so for neurologically intact people can improve the accuracy of goal-directed reaching in the absence of ongoing visual feedback, and eliminate limb position drift during limb stabilization without visual feedback. Doing so for stroke survivors who retain some motor strength and the capacity to produce flexion and extension torques in the proximal involved arm could promote increased use of that arm by allowing them once again to "feel" movement, thus enhancing arm control in the absence of visual feedback.

Although a focus on neural mechanisms is beyond the scope of the current study, we note that vibration and joint position sense both follow the dorsal column/medial lemniscus system that projects through the ventral posterior lateral nucleus of the thalamus to primary sensory cortex. As shown via functional neuroimaging (Suminski et al. 2007; Scheidt et al. 2012), these brain regions contribute importantly to the real-time, closed-loop control of the distal upper extremity. They are also susceptible to injury from the most common form of stroke. Recent studies reveal networks of neurons interconnecting two sides of the gray matter at the brainstem and spinal levels as well as intrahemispheric transcallosal connections that may form “detour circuits” for recovery of function [for review, see (Jankowska and Edgley 2006)]. We therefore speculate that "detour circuits" may provide a way for the supplemental kinesthetic feedback we describe to tap into residual cerebello-thalamo-cortical circuits that participate in the real-time, closed-loop control of the contralesional arm and hand.

Participants in the current study perceived error feedback to be more useful than state feedback during the reaching task, but exhibited no clear preference for either form of feedback while stabilizing about the home target. This outcome makes sense because state and error feedback were virtually identical at the home target in both tasks. Either spontaneously or during the survey period at the end of the session, every participant in Experiment 2 reported that they preferred the presence of informative vibration during training and test phases over no vibration. Many participants expressed dismay or frustration when asked to repeat the task without vibration after they had been able to practice with vibration. These subjective results reflect positively on the user experience of wearable technologies using vibrotactile encoding of state and/or error feedback for the purpose of enhancing motor performance of goal-directed actions with the arm.

A limitation of our approach is that we were unable to identify in all participants a common configuration of the vibrotactile display that would allow effective discrimination between activations within all tactor pairs. Instead, tactor placements had to be individualized in 16 of the 26 participants. Even though these 16 participants could initially feel each tactor when individually activated, they reported that for some pairs, they only felt one tactor vibrating even when both were turned on. The most common difficulty was interference between the upper arm and forearm tactors. Adjusting the upper arm tactor slightly to the right or to the left usually resolved this issue. In some cases the forearm tactor instead had to be shifted. 1 participant did not complete the study and was replaced because she could not discriminate tactor vibrations despite multiple tactor adjustments. We suspect that these difficulties were attributable, in part, to normal variations in the distribution of dermatome innervations across individuals (Lee et al., 2008). Another common difficulty was that the internal forearm tactor felt “dull”. This was typically resolved by shifting the tactor around the muscle or distally towards the wrist. Some participants reported the hand tactor felt much stronger than the other tactors. This perception was reduced by moving the hand tactor towards the wrist. For most participants, adjusting the tactor(s) by 1 to 2 centimeters was enough to fix the problem. Preliminary psychophysical studies using the same tactors as in the present study suggest that there are indeed systematic differences in vibration perception (discriminability) across dermatomes in healthy human subjects (Shah et al. 2016a, 2016b). However, in the current study, a few participants demonstrated variability in vibrotactile perception between sessions such that tactor placement needed to be adjusted from one session to the next. Future work should explore the impact of location-dependent variations in vibrotactile perception and sensorimotor control, and we recommend future applications to attend carefully to this source of variability.

3.5 Conclusions

The results of this study have established the immediate utility and relative merits of two forms of vibrotactile kinesthetic feedback in enhancing stabilization and reaching actions performed with the arm and hand in neurotypical people. Whereas the first set of experiments identified one specific combination of hand position and velocity information that optimized state feedback control of stabilization and reaching actions after very limited practice, the second set found that error feedback – a simple form of "goal-aware feedback - yielded superior performance relative to optimized state feedback throughout the reachable workspace. These results are important because they demonstrate that the intact human brain is capable of integrating vibrotactile kinesthetic feedback into the ongoing control of the moving arm and hand, even when that feedback is applied to a body part not directly involved in the action (i.e., the other arm). These findings provide strong empirical evidence motivating and guiding future development of sensory substitution technologies seeking to counteract impaired proprioceptive sensation in stroke survivors who retain motor capacity in the more involved arm.

Chapter 4: Control bandwidth in healthy participants

4.1 Introduction

Goal-directed reaching behaviors are thought to be comprised of at least two different control actions: trajectory control and end point position stabilization (Scheidt and Ghez, 2007; Ghez et al., 2007; Scheidt et al., 2011). Stabilization tasks (described in the previous chapter) emphasize the use of vibrotactile feedback for end point position control whereas reaching tasks allow (and promote) the integration of vibrotactile feedback into both components of control. Here, we consider a third task, tracking a moving target, which emphasizes the integration of vibrotactile feedback into the ongoing control of movement trajectory while minimizing the occurrence and utility of limb postural stabilization. Moreover, by increasing the speed of the moving target, it is possible to identify the limits of sensorimotor processing (i.e., the bandwidth of control) while using supplemental vibrotactile feedback. Specifically, the speed at which a participant can no longer track a moving target using vibrotactile feedback provides useful information about the upper limit of the rate of sensorimotor information processing for movement control in the state and error feedback conditions.

4.2 Methods

Fifteen participants (8 Female) participated in 2 experimental sessions at least 2 hours apart (Range 2 hours to 19 days; mean 5±6 days). Both sessions followed the same experimental protocol but used a different type of feedback, *optimal limb state feedback* or goal-aware *error* *feedback* (see Chapter 3). The presentation order of state and error feedback sessions was counterbalanced across participants. The experiment sought to determine the maximum bandwidth of sensorimotor information processing in the two supplemental kinesthetic feedback conditions using a continuous tracking task.

Participants were seated comfortably in a chair in front of the horizontal planar robotic manipulandum (see chapter 3 and Casadio et al. 2006) (Fig 3.2), approximately 25 cm from the center of the physical workspace. The right arm was securely strapped to the robotic handle and its integrated arm support. The seat height was adjusted such that the abduction angle of the right shoulder was between 75° and 85°. The left arm rested comfortably on a horizontal planar armrest situated below that plane of motion of the robot. An opaque shield was placed over the workspace to block the participant's view of the moving arm and the robotic apparatus. View of the stationary arm was not precluded. A vertical computer monitor was mounted in direct view which provided visual cues of hand and target position and motion when appropriate (the scheduling of visual feedback is described below). The mapping of hand displacements within the robot workspace to cursor displacements on the computer monitor display was 1:1. The cursor had a 0.5cm radius and continuously tracked the motion of the hand at all times while it was visible (the scheduling of cursor visibility will be described below). The tasks and experimental protocol are implemented using Python (Python Software Foundation) and H3D API (SenseGraphics, www.h3dapi.org). H3D is an open-source application program interface (API) designed for 3D haptics and graphics design that allows users to add various pre-made haptics and graphics objects to the workspace. This study used a 2D workspace within H3D since the horizontal planar manipulandum has a 2D workspace.

Supplemental kinesthetic feedback was provided using a two-channel (4 "tactor") vibrotactile display attached to the non-moving arm. For all participants, tactors were initially arranged with one tactor on the back of the hand, two tactors on the forearm, and one on the upper arm (Fig 3.2; default tactor locations indicated by red spheres). Elastic fabric bands were used to secure the tactors to the arm and hand. We then performed a verification procedure wherein we adjusted tactor locations slightly so that each participant could indicate reliably which tactor or pair of tactors was activated at any given time. This was done with both low and high intensity vibrations. This setup procedure successfully identified well-discriminated stimulation sites in all participants and typically took about 10 minutes to complete. The verification procedure began by asking the participant to pause at each of the four corners of the screen and tell the experimenter how many and which tactors were vibrating. This was repeated near the center and approximately mid-way between the center and the edge of the screen. Next, the participant was asked to pause at the middle of the screen, and then move away from and back towards the center to feel the changing intensity. If the participant gave incorrect or uncertain answers at any point, further personalized tests were used to isolate and resolve the problem.

The vibrotactile display was calibrated to the robot's workspace such that motions of the robot handle to the right would induce the +X tactor to vibrate, whereas motions of the robot handle away from the participant (i.e., toward the monitor) would induce the +Y tactor to vibrate. Three types of vibrotactile mappings were used. In the first, limb state feedback, the feedback was a combination of the position and velocity of the cursor. The center of the vibrotactile workspace was the center of the screen and robot workspace, the feedback was only off if the cursor was at rest at the center of the screen. Vibratory stimulation reached 90% full scale range (FSR) when the hand reached the bounds of the visual display (corresponding to a displacement of 15 cm from the center). In the second, error feedback, the feedback was the instantaneous signed error between the hand and target locations. The feedback was always 0 (i.e. tactors off) when the cursor was on the target and increased in direct proportion to the vector error between the hand and the edge of the target. In the third, sham vibration, the tactors were cycled randomly and the feedback was irrelevant to the task (see chapter 3 for details about the construction and content of the sham signal).

A reaching task and a stabilization task were used to train the participants on the vibrotactile display. During the reaching task, participants performed out-and-back reaches to 16 targets distributed around a central home target. During the stabilization task, participants attempted to hold the robot handle steady at the center of the workspace against robotic perturbations for 60 seconds. (Detailed information about reaching and stabilization tasks, the experimental setup, and feedback encodings may be found in Chapter 3, which describes and analyses the reaching and stabilization portion of this experiment). Training tasks typically took 40 minutes to complete.

In the continuous tracking task used for testing, a 1 cm target moved counter clockwise around a circular path, centered on the home location (i.e. the center of the workspace), with an inner radius of 3cm and an outer radius of 7cm. A robotically imposed force wall limited the cursor to the bounds of the circular path. The force wall was haptically implemented on the robot using the H3D Torus object with the FrictionalSurface enabled (FrictionalSurface parameters were stiffness=1200 N/m, damping=0.1 Ns/m, staticFriction=0.1, and dynamicFriction=0.1). The target always started from a position directly to the right of the center. The trial began when the participant placed the 0.5 cm cursor within the target and a 3-second countdown was initiated (signaled by both audio and visual cues). When the countdown ended, the target started moving in the counter-clockwise direction at a very low frequency of 15°/s, which increased linearly with time at a rate of $15°/s^2$ up to a maximum possible speed of 815°/s (i.e. up to a maximum of 1 minute and 51 laps per trial). Participants were instructed to "Maintain the hand within the target as long as possible." The tracking task was designed to assess the point where the participant could no longer track the target, (i.e., the upper limit of movement control or the bandwidth of control). Failure was defined as the number of laps (or equivalently, the point in time, or the rotational frequency) where the hand is lapped by (or laps) the target (i.e., when the hand falls 360° behind or advances 360° ahead of the target). Once the point of failure occurred, the target completed the current lap and then came to rest at the starting position. A message on the screen instructed participants to rest for 45 seconds. Then, the message disappeared, the participant was instructed to move the cursor to within the target, and the countdown for the next trial began. Each attempt at the tracking task included two trials. The number of laps completed for each trial were averaged to yield a single measure of tracking performance per task attempt.

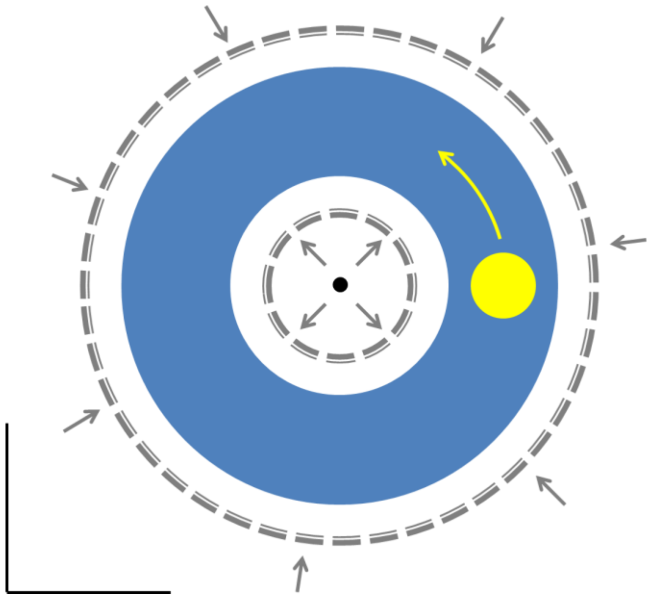

Figure 4.1: Tracking task setup. The yellow target moves counterclockwise around the blue track. The grey lines and arrows represent the invisible repelling force generated by the robot if the participant left the bounds of the blue track. The center of the blue track (i.e., black dot, not visible to participants) is the center of the physical robotic workspace, the center of the visual workspace, and the origin of the state vibration map of space. The black bars represent 5 cm.

During the state feedback session, three visual feedback conditions were used (Table 4.1). In the first condition (continuous visual feedback; V_+), the cursor was always visible on the computer screen and tracked the motion of the hand continuously. In the second feedback condition (no visual feedback; V_-), participants attempted to track the target without ongoing cursor feedback (i.e., the cursor was never visible). In the third visual feedback condition (Knowledge of Results; V_{KR}), participants only received cursor feedback of hand position after the trial was complete. During these feedback conditions, the target was continuously visible.

During the error feedback session, an additional target visibility condition was added. Error feedback is "goal-aware" in the sense that vibrotactile feedback of performance error explicitly includes information about the target location. In the case of error feedback, the visual target and the vibrotactile information provide redundant information about the position of the target. In order to encourage the use of the vibrotactile feedback, in some blocks the visual target (G) followed the knowledge of results condition (G_{KR}) in which the target was only visible after each trial was complete (Table 4.1). In all other blocks the target was continuously visible. The same three visual conditions (V_+, V_-, V_{KR}) were used for the cursor (V).

\Block Session	Familiari-zation	Baseline (pre-testing)	Training	Check	Baseline (post-testing)	Test	Sham
State	V_+T_-	V_-T_-	$V_{KR}T_+$	$V_{KR}T_+$	V_-T_-	V_-T_+	V_-T_S
Error			$V_{KR}T_+G_{KR}$				$V_-T_SG_{KR}$

Table 4.1: Sequence of visual and vibrotactile feedback conditions during the state and error feedback sessions. Participants completed one reaching task, one stabilization task, and one tracking task for each block, and in “Training” they performed four additional reaching tasks. The grey columns highlight the blocks where the visual feedback conditions differed between the state and error feedback sessions. “V” indicates visual feedback of the cursor. “T” indicates vibrotactile feedback. “G” indicates visual feedback of the target. “+” indicates continuously available. “-“ indicates never available. “KR” indicates only visible at the end of each trial for knowledge of results.

During each session, participants completed a series of reaching, stabilization, and tracking tasks guided by various combinations of cursor visual feedback (V), target visual feedback (G) and vibrotactile feedback (T) (Table 4.1). First, participants familiarized themselves with each task by practicing each with continuous vision without vibratory feedback (V_+T_-). Participants then repeated the tasks with neither a visible cursor nor vibration feedback (V_-T_-) in order to assess baseline performance before vibration training. Following baseline assessment, participants were introduced to the vibrotactile display and encouraged to freely explore the workspace for up to 3 minutes. Participants then received training throughout the workspace by performing five sets of 32 reaches and one stabilization trial with vibrotactile feedback and visual knowledge of results of the cursor ($V_{KR}T_+$). During training trials with state feedback, the target was continuously visible. During training trials with error feedback, the target was visible only after the end of the trial (i.e., visual knowledge of results; $V_{KR}T_+G_{KR}$) since error feedback explicitly includes information about the target location. On average, participants took 45 minutes to do this training. Next, in order to check for any differences in performance due to the target visibility in error feedback, we asked participants during the error session to perform the reaching and stabilization tasks once with the target continually visible ("check" block; $V_{KR}T_{+}$) in order to compare with the training where the target was only visible for knowledge of results ("training" block; $V_{KR}T_{+}G_{KR}$). To equalize the time spent using the feedback, during the state feedback session the participants simply repeated the training tasks and conditions during the check block. Then, participants repeated the baseline for each task without cursor visual feedback or vibrotactile feedback ($V_{-}T_{-}$) in order to identify any practice effects. Next, participants performed the test, in which they did each task once using vibrotactile feedback without any visual feedback of the cursor ($V_{-}T_{+}$). Lastly, participants performed each task while receiving task-irrelevant sham vibration. For the sham block during the state session, the cursor was never visible and the target was always visible ($V_{-}T_{+}$). For the sham block during the error feedback session, the cursor was never visible and the target was only visible for knowledge of results ($V_{-}T_{S}G_{KR}$) since the uninformed participants expected the vibration to still deliver accurate error feedback, including the target location.

4.3 Results

Some participants required adjustments to the default tactor locations in order to be able to well perceive and discriminate each tactor (see chapter 3 for details on the difficulties some participants initially encountered with tactor placement). Ultimately, all participants were able to perceive and discriminate one or more tactors turned on at the same time for at least high and low intensities. All participants attentively attempted the tracking task. Some participants found the higher speeds as the tracking trial progressed to be tiring for the moving arm, but recovered quickly with 30 seconds or 1 minute of rest and were able to comfortably proceed with the next task.

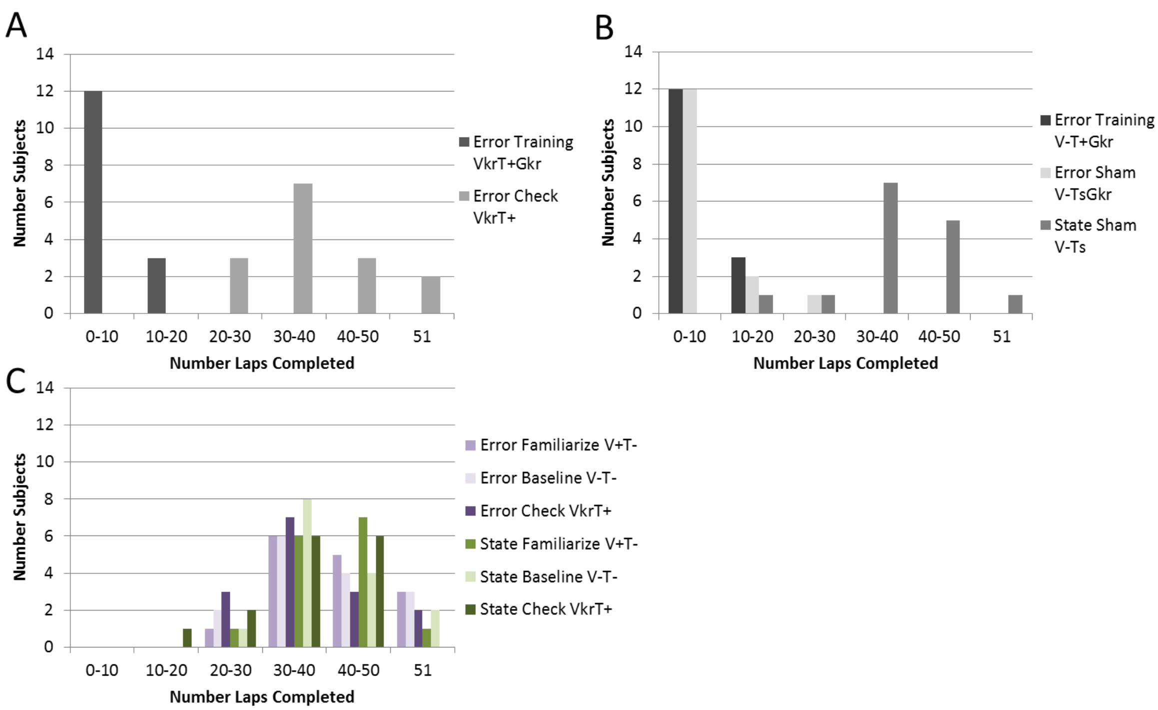

Figure 4.2: The factor determining performance is the target visibility; the presence or content of vibrotactile feedback did not affect performance, suggesting participants were ignoring it. (A) The target visibility dramatically affects the performance as shown in the error feedback training and check blocks where the vibration and cursor visibility remain the same and the only difference is the target visibility. (B) The target visibility dramatically affects the performance and the vibration encoding does not. For the two blocks using different vibration but both without target visibility (Error V-T+GKR and Error $V_-T_SG_{KR}$) , the performance does not vary and is poor. For the two blocks both using sham vibration (Error $V_-T_SG_{KR}$ and State V_-T_S) the only difference is the target visibility and the performance is very different. The performance depends only on the target visibility, the participants performance does not depend on the vibration encoding. (C) The cursor visibility or the presence or content of vibratory feedback does not affect performance. Similarly high performance is seen regardless of the presence of the cursor (visible in familiarization, not visible in baseline, only visible at the end of each trial for check) and regardless of the presence or type of vibratory feedback (no vibration in familiarization or baseline, either state or error vibration in check).

During the training with error feedback when the target was not visible ($V_{KR}T_+G_{KR}$, Fig 4.2-A, dark bars). the performance is poor in that participants could not complete many laps (average < 10 laps). However, during the check block with error feedback, when the target was visible ($V_{KR}T_{+}$, Fig 4.2-A, light bars), the performance improved (average > 30 laps). The only protocol difference between these two blocks was the target visibility; when the target was visible the performance was good and when the target was not visible, the performance is poor. This indicates that the target visibility is a factor that effects task performance.

Next, we compared sham vibration from the state and error sessions, in which the target was visible for the block preceded by state feedback, but not visible for the block preceded by error feedback (Fig 4.2-B, Error $V_{-}T_{s}G_{KR}$ vs State $V_{-}T_{s}$). We see poor performance in the error session sham block when the target was not visible (i.e., low number of laps completed), but we see good performance in the state session sham vibration when the target was continuously visible. In both cases the vibration was the same and the only difference was the target visibility. This adds further support for the idea that the target visibility matters for performance in the tracking task. Additionally, during the error session, the performance during the training block with the error vibration was the same as the performance during the sham block (Fig 4.2-B, Error $V_{-}T_{+}G_{KR}$ and Error $V_{-}T_{s}G_{KR}$).In both of these blocks the target was not visible, and the performance was poor. Even though one block provided relevant feedback information and the other provided random (irrelevant) feedback information, the performance was poor in both cases because the target was not continuously visible. This indicates that the performance differences seen in the tracking task were primarily dependent on target visibility and not on the vibration content.

Finally, subjects were able to complete a large number of laps during the familiarize, baseline, and check blocks of both error and state vibration conditions, during which the target was always visible (Fig 4.2-C). There were no significant differences in performance for the familiarization, baseline, or check blocks for either state or error feedback. The performances were similarly good whether or not the cursor was visible, whether or not vibrotactile feedback was provided, and whether the feedback was error or state encoding. This suggests that cursor feedback, i.e. visual feedback of hand position, was not important for performance in the task. Likewise, the presence of vibration did not contribute meaningfully to tracking performance. All together, the results shown in Fig 4.2 A-C demonstrate that performance was driven primarily by the target visibility, and not by the content of the vibration feedback, the presence of vibration feedback, or the presence of visual hand position feedback. Thus target visibility confounded any differences that might have existed due to the vibration feedback in the tracking task.

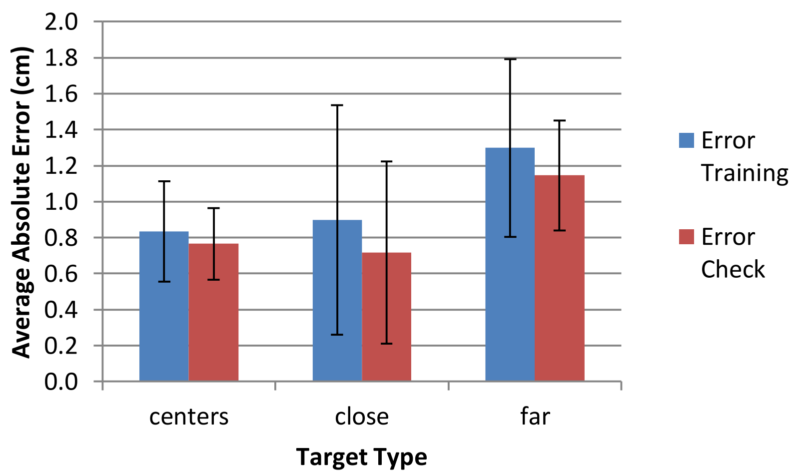

Figure 4.3: For all three target types, the average absolute error was similar for error and state feedback. The target was not visible during the training ($V_{KR}T_{+}G_{KR}$) and was visible during the check ($V_{KR}T_{+}$). Since the performance did not differ between the blocks (red or blue color), the target visibility did not significantly impact the average absolute error during the reaching task. Error bars are ± standard deviation.

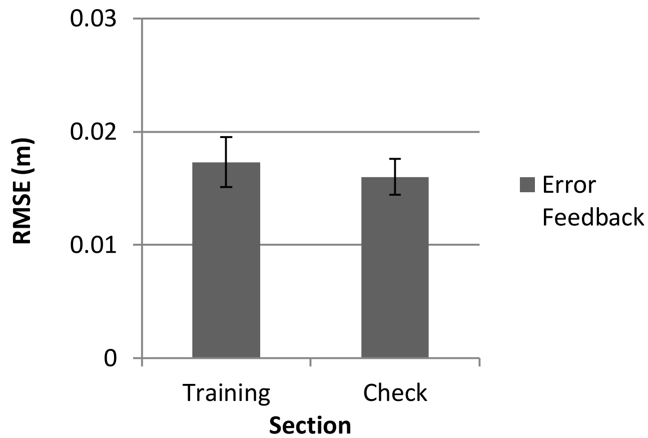

Figure 4.4: Stabilization performance was not dependent on target visibility. RMSE was similar in the training block without target visibility, $V_{KR}T_{+}G_{KR}$, and in the check block when the target was visible, $V_{KR}T_{+}$. RMSE did not differ with block, and therefore stabilization performance was not affected by the target visibility. Error bars are ± 1 SEM.

Importantly, the reaching task does not show any significant effects from the target visibility (Fig 4.3). For all three target types, the average absolute error was similar for error and state feedback. The target was not visible during the training ($V_{KR}T_{+}G_{KR}$) and was visible during the check ($V_{KR}T_{+}$). Since the performance did not differ between the blocks (red or blue color), the target visibility did not significantly impact the average absolute error during the reaching task. In the stabilization task (Fig 4.4), the RMSE did not differ between training and check blocks, in which the only difference was target visibility, suggesting the stabilization performance was not dependent on the target visibility. Thus, the tracking task was the only task in which target visibility was a driving factor for performance.

4.4 Discussion

The tracking task aimed to investigate and quantify the sensorimotor limits of arm control when using state and error vibrotactile feedback. The tracking task did not yield quantitative information about how participants can use the vibration. The results show that participant performance depended primarily on target visibility (Fig 4.2 A-C) and participants likely did not use the vibrotactile information to control their movements. The design of the task did not sufficiently challenge the innate abilities of the participants as the robotic force walls limited the accumulation of natural proprioceptive drift and therefore intrinsic schemes were likely sufficient to complete the task without using the vibrotactile feedback. The short practice times and force wall design further obscured the performance effects of the state and error vibrotactile feedback encodings. Patient perspectives offer insights into the task, and a number of alterations for future studies are suggested so that this task can be successfully used to identify the control bandwidth when using vibrotactile feedback.

The fact that familiarization and baseline performance yielded uniformly high numbers of completed laps (and thus, high sensorimotor control bandwidths), even after ongoing cursor feedback was removed, shows that the design of the task did not sufficiently challenge the innate abilities of the participants. In the reaching and stabilization tasks, performance degraded when visual cursor feedback was removed (see chapter 3), unlike what was seen here with the tracking task. The reaching and stabilization tasks thus worked well in healthy participants for testing use of the vibrotactile feedback because participants could not rely only on their innate proprioception to solve the problem (something that our target stroke population also cannot do), but instead had to try to use the vibrotactile feedback to solve the task. However, in the tracking task the performance remained the same when visual cursor feedback was removed, indicating that innate abilities were sufficient to solve the task and therefore participants did not need to use the vibrotactile feedback. I believe this outcome was due to a design flaw in the experimental conditions.

The robotic force walls likely constrained the tracking task to such an extent that participants did not actually need to resolve hand location with precision in order to perform the task. Satisfactory performance could be obtained by simply moving the shoulder and elbow joints within the force walls in an approximately cyclical and appropriately-phased manner. The inner force wall was added during pilot testing to impose a minimum diameter to prevent participants from collapsing about the origin as their speed increased. The outer force wall was added to keep participants in the workspace as some pilot participant's movements became very large at higher speeds. However, these walls essentially reduced this task to one degree of freedom *in order to complete the circle.* Though two degrees of freedom were still technically involved in staying on the target; radial position became nearly irrelevant when there was a small target and higher speeds as the participants focused on completing the circular motion and merely staying near the target. Thus, it essentially became a one degree of freedom task. The presence of the robotic force walls constrained the user to generate hand paths that had the correct radius and that were correctly centered in the workspace. By "over-constraining" the tracking task, the force walls eliminated the accumulation of drift, effectively eliminating the key performance deficit typically observed in neurologically intact participants that made it possible to demonstrate utility of supplemental kinesthetic feedback in the reaching and stabilization tasks.

Without the need for precision and without the accumulation of proprioceptive drift, the presence of the moving target in conjunction with intact proprioception may have allowed participants to solve the tracking task in the absence of cursor feedback by using a multisensory integration scheme like that described by Deneve and Pouget (2004). In their simulation study, Deneve and Pouget used a Bayesian framework to describe the integration of multiple sensory inputs with adjustable weights relative to the situational reliability of each sense. They proposed that integration involves “translation” of one sensory modality (and mapping) into another, rather than a convergence of the multiple modalities (and mappings) into a separate representation. Thus, the presence of the moving visual target (in retinal coordinates) could have been mapped onto a virtual physical target (in joint space coordinates), which could then be used to drive performance in the tracking task. Equivalently, the presence of intact proprioception (in joint space coordinates) could have been mapped to a virtual visual representation of hand position (i.e. a virtual visual cursor) (in retinal coordinates), which could likewise have been used to drive performance in the tracking task. Either of these situations would allow participants to retain good performance in the absence of cursor feedback, as was seen in our data. As a result of such a multisensory integration scheme combined with the flaws in task design, participants likely simply ignored the vibrotactile feedback and were still able to perform well in the tracking task.

Additionally, other cognitive strategies could have been encouraged by the presence of the force walls. For example, during a block without vibrotactile feedback I observed one participant using the direction of the forces from the force walls to find the starting location again. The ability to use such haptic cues to localize the hand in space was not available in the reach and stabilization tasks. Though I intended the force walls to constrain the tracking task to be accomplishable by all participants, this design feature enabled participants to use innate somatosensory feedback to achieve unforeseen solutions. As designed, the tracking task could be too well resolved using innate proprioception and multisensory integration schemes, thus precluding any need to use the novel supplemental vibrotactile feedback.

4.4.1 Participant perspectives

Though I was unable to compare performance based on error, state, or sham feedback, the observations of the participants are enlightening. Discussion with the participants suggests that state vibrotactile feedback may be useful in different ways for static or moving targets. At higher tracking speeds with state feedback, this task demanded focus on a pattern of movement rather than focus on small adjustments to center on the target. As one participant said, “It helped in keeping a rhythm as the vibration moved around arm”, and another said they “tried to have a vibration pattern that matches the pattern of the moving target”. In reaching or stabilization, the presence and strength of vibration *within* each tactor is important and useful. In a tracking task at higher speeds, the patterns of change in vibration *between* tactors may become more important as the participant seeks to complete a particular pattern of vibration with a certain time course.

At least three participants trying to use the vibration during error feedback when the target was not visible found it was cognitively difficult to follow the target’s motion based on the vibrotactile information. The participants reported it took too long to extract the target position from the vibrotactile information; “It’s changing every second. By the time I figure out what the vibration means the target has moved. My processing time is too slow”, and “the target is moving, so you localize it but then it’s gone”. Such statements suggest that the participants were operating well above their bandwidth of control when the task elicited their comments. Alternatively, or concurrently, participants had not yet learned how to apply vibrotactile information to a moving target. Importantly, the participants only practiced the tracking task with vibrotactile feedback for less than 10 minutes each session. Longer practice times could help participants better learn how to use the vibrotactile feedback for the tracking task, thereby improving performance bandwidth.

4.4.2 Conclusions and future directions

In conclusion, this task failed to yield quantitative data about control bandwidth in the two feedback conditions due to the confound of the visibility of the target and the suspected limitations imposed by the force wall. However, this task highlights the importance of the participant's strategy and of the environment in which we research sensory substitution. For the tracking task with a moving target, the differences seen between and within error, state, and sham vibration, are entirely explained by the target visibility. For our healthy participants, vision of the target provided all the information needed to complete the task, even without the cursor, at least in part due to the force wall. Intended to constrain the task, the force wall had the effect of effectively reducing the task to one dimension, particularly at higher speeds where staying centered on the target is less important (or achievable) than completing the circular pattern at the appropriate speed. As shown by the performance in the baseline without cursor or vibration feedback, most participants were still able to complete the task well due to the target visibility, multisensory integration schemes, and the force wall. In order to assess the utility of vibration feedback for tracking or moving targets, future experiments will need to redesign the task to eliminate the confounds, allow for the accumulation of natural proprioceptive drift, and isolate the performance of the vibrotactile feedback from other participant strategies.

I suggest that future studies remove both force walls and replace them with visual walls and an additional failure condition. In this case, participants would also fail the task if they failed to maintain a certain distance about the origin or exceeded a certain distance from the origin, i.e. essentially replacing the physical walls with software bounds. In this manner, we can retain the intent of the force walls (i.e. to prevent movements from becoming excessively large and wild or tiny as seen in pilot subjects) while ceasing to provide unintended haptic information to the participants and allowing the accumulation of proprioception drift. In this case, the participants would need to use the vibration to correct for their natural accumulation of drift, or their drifting position would violate the software bounds and the trial would be over. Additionally, I suggest that the moving target begins much slower, to be sure to include the bandwidth of all participants when using vibrotactile feedback. Lastly, I suggest that training for this task is changed to involved moving targets instead of static targets, since participant comments suggest state vibrotactile feedback may not be used in the same manner for both types of targets. For example, having participants first practice following a target moving along a straight line and a diamond might help participants become comfortable using each type of vibrotactile feedback for dynamic targets and remove this potential confound.

Chapter 5: The use of vibrotactile feedback in stroke survivors

5.1 Introduction

Almost 50% of stroke survivors experience impaired limb position sense in their contralesional arm (Carey and Matyas 2011; Dukelow et al. 2010; Connell et al. 2008). Loss of kinesthetic sensation contributes to impaired control of reaching and stabilization behaviors (Scheidt and Stoeckmann 2007; Zackowski et al. 2004) that are vital to an independent life style (Blennerhassett et al. 2007; Tyson et al. 2008). Many activities of daily living, such as using a utensil to retrieve food from a plate, require the coordination of reaching and stabilization behaviors. As a further step towards the larger goal of enhancing or restoring closed loop kinesthesia feedback in stroke survivors suffering from impaired kinesthetic sense, I performed a set of case studies in which stroke survivors attempted to use vibrotactile feedback to enhance goal-directed actions performed with the arm and hand.

In neurologically intact individuals, control of reaching and stabilization behaviors may be composed of two independent control actions specifying movement trajectory control and end point stabilization (Scheidt and Ghez, 2007). After stroke, it is possible that these control pathways for the impaired arm are compromised, in which case, sensory substitution and supplemental feedback therapies are not likely to improve performance in stroke survivors. However, in some survivors, it is possible that descending control pathways remain relatively intact, and impaired sensorimotor function in the move-involved arm is instead due to impaired or absent kinesthetic input. If this is the case, feedback therapies, including sensory substitution, may be able to improve function. In the following series of case studies I investigated the extent to which stroke survivors can use (and learn to use) limb state and goal-aware supplemental vibrotactile feedback. Here, I build upon the results of the experiments with healthy adults and provide a proof of concept for what may be possible after stroke. Together, these examples will provide guidance for future work seeking to mitigate the negative impact of post-stroke kinesthesia deficits by creating real-time sensory substitution technologies.

5.2 Methods

Five stroke survivors gave written informed consent to participate in a series of three primary experimental sessions designed to evaluate the utility of state and error feedback for enhancing control of end point stabilization and movement trajectory after stroke (Table 5.1). All procedures were approved by local Institutional Review Boards serving the University of Genoa (ASL3 Genovese) and Marquette University in accord with the 1964 Declaration of Helsinki. Inclusion criteria include adults in the chronic stage of recovery (>6 months post-stroke), a range of horizontal upper limb movement exceeding 10cm, the ability to understand and follow basic two-step instructions, and impaired or absent proprioception in the ipsilesional arm. Exclusion criteria include absence of vibration sensation in the less-impaired arm and neurological impairments that prohibit informed consent, understanding of the task, or ability to perform the required tasks. Two of the participants completed a preliminary exploratory session five months prior. The primary experimental study consisted of one visit to the lab for clinical testing and then two, 1-hour-long experimental sessions, all within a three week period.

Subject ID	General Data						
	Gender	Paretic hand	I/H	Site of lesion	Age (yrs)	Time since stroke (yrs)	Notes
S01	F	R	I	left basal ganglia, internal capsule and occipital lobe	68	12.5	Tremor
S02*	F	L	H	Right occipital	65	16	No neglect diagnosis
S03	M	L	I	Right basal ganglia, temporal lobe and insula	57	1	Difficulty in extension
S04*	F	L	H	Right fronto-parietal prerolandic	64	10	
S05	F	R	I	Left basal ganglia, internal capsule, temporal lobe and insula	61	7	

Table 5.1: Characteristics of participants, I = ischemic, H = hemorrhagic. Asterisks * indicates participants who participated in pilot testing 5 months prior to the experiments reported in this chapter.

Subject ID	FMA						MAS						CAHAI (0-91)
	A (0-36)	B (0-10)	C (0-14)	D (0-6)	A-D (0-66)	H (0-12)	shoulder (0-4)	elbow (0-4)	forearm (0-4)	wrist (0-4)	fingers (0-4)	thumb (0-4)	
S01	31	10	13	3	57	11	1	0	0	0	0	1	80
S02	31	6	5	0	42	7	1	1	1	2	1	1	24
S03	5	0	0	1	6	7	1+	1+	2	3	3	3	13
S04	10	4	2	1	17	2	2	1	1	1	1+	1	29
S05	14	2	2	3	21	12	1	3	2	1	1	1	13

Table 5.2: Clinical scales for motor and functional ability. FMA = Fugl-Meyer Motor Assessment, MAS = Modified Ashworth Scale, CAHAI = Chedoke Arm and Hand Activity Inventory. Numbers in parentheses are the range of possible scores. Higher FMA and CAHAI scores indicate higher motor and functional ability; higher MAS scores indicate higher spasticity.

Subject ID	NSA		Tuning Fork			
	Proprioception (0-3)	Stereognosis (0-2)	Impaired arm (≥6.5 is "normal")		Less impaired arm (≥6.5 is "normal")	
			Elbow	Wrist	Elbow	Wrist
S01	3	2	6	6	6	6
S02	1	0	5	6	6	6
S03	0	0	6	5.5	7	7.5
S04	0	0	6	5.5	4.5	6
S05	3	0	7.5	7.5	7.5	7

Table 5.3: Clinical scores for perception. NSA = Nottingham Sensory Assessment. Numbers in parentheses are the range of possible scores. Higher NSA and Tuning Fork scores indicate higher ability.

The first visit to the lab was composed of informed consent and clinical testing (Tables 5.2, 5.3). We used the Fugl-Meyer Upper Limb Assessment (FMA) sections A-D and H to evaluate motor function in the impaired arm. We used the Modified Ashworth Scale (MAS) to quantify spasticity. We used the Chedoke Arm and Hand Activity Inventory (CAHAI) to evaluate functional ability in activities of daily living. The kinesthetic and stereognosis portions of the Nottingham Sensory Assessment (NSA) and a tuning fork were used to evaluate somatosensation. We used the Mini Mental State Examination (MMSE) to screen for gross deficits in cognitive function. For all tests, a higher number indicates a higher level of the tested item (e.g. higher FMA means higher motor function, higher MAS means higher spasticity). All clinical tests were completed by an experienced physical therapist.

For the first and second experimental sessions, participants performed reaching and stabilization tasks while receiving supplemental kinesthetic state feedback and error feedback. Three participants received state feedback first, while the other two received error feedback first. Four of the five participants completed all three sessions. The fifth participant (S05) was unable to return for the third session, and thus completed only two sessions.

Subject	Session	Feedback	Familiarize V+T-	Practice VkrT+	Baseline V-T-	Test V-T+	Sham V-Ts
S01	1	State	✓	✓✓	✓	✓	✓
	2	Error		✓✓	✓	✓	✓
S02*	1	State	✓	✓	✓		
	2	Error		✓✓✓		✓	
	3	Error		✓✓✓	✓	✓	
	4	Error		✓✓		✓	
S03	1	State	✓	✓✓	✓	✓	
	2	Error		✓✓		✓	
S04*	1	Error	✓	✓			
	2	State		✓✓			
S05	1	Error	✓	✓	✓		

Table 5.4: Protocol for each participant and vibrotactile session. Each block includes one reaching task and one stabilization task. The number of checkmarks indicates the number of

repetitions; for the practice block two repetitions were standard. Prior to the first experimental session, participants visited the lab and were evaluated using clinical scales, but did not use vibrotactile feedback. Note participants indicated with an asterisk (*) (S02 and S04) completed a preliminary experimental session 5 months prior in which they practiced reaching and stabilization with error and state feedback.

Participants were seated comfortably in front of the robotic manipulandum (Fig 3.2A). The participant was seated with the impaired arm strapped to the robotic handle and its integrated arm support. The chair was adjusted so as to center the patient's physical workspace at the center of the robotic workspace. The left arm rested comfortably on a horizontal armrest. An opaque shield was placed over the workspace to block the participant's view of the moving arm and the robotic apparatus. View of the stationary arm was not precluded. A flat foot rest was provided. A vertical computer monitor placed in direct view of the participant provided visual cues of hand and target position and motion when appropriate (the scheduling of visual feedback is described below). The mapping of the robotic handle movement to the cursor movement was 1:1. Participants were not given explicit instructions regarding where to direct their gaze.

Supplemental kinesthetic feedback was provided using a two-channel (4 "tactor") vibrotactile display attached to the non-moving, less-impaired arm. The vibrotactile display was calibrated to the robot's workspace such that motions of the robot handle to the right would induce the +X tactor to vibrate, whereas motions of the robot handle away from the participant (i.e., toward the monitor) would induce the +Y tactor to vibrate.

All sessions began with a set-up procedure which took approximately 5-10 minutes. During set-up, the four tactors were initially arranged on the non-moving arm with one tactor on the back of the hand, two tactors on the forearm, and one on the upper arm (Fig 3.2A; default tactor locations indicated by red spheres). If necessary, we adjusted tactor locations so that each participant could indicate reliably which tactor or pair of tactors was activated at any given time. This was done using low, middle, and high intensity vibrations (approximately 10%, 40% and 90% full scale range, respectively). The adjustment / verification procedure began by asking the participant to place the hand's cursor at each of the four corners of the screen and to tell the experimenter how many and which tactors were vibrating (at ~90% FSR). This was repeated two times, once near the center of the screen (~10% FSR) and again approximately mid-way between the center and the edge of the screen (~40% FSR). Next, the participant was asked to place the hand's cursor at the middle of the screen, and then to move away from and back towards the center so as to feel the changing intensity. If the participant could not give clear and correct indication as to which tactor was active and the appropriate direction of activation change, further personalized tests were used to isolate and resolve the problem. Verbal feedback was encouraged from all participants throughout the experiment and participants were encouraged to ask questions and describe their ongoing experience.

Three types of vibrotactile mappings were used. In the first, *limb state feedback*, the tactors encoded a weighted combination of position and velocity of hand motion. The center of the vibrotactile workspace was aligned with the center of the visual screen and the center of the robot's physical workspace. All tactors were "off" only if the cursor was at rest at the center of the screen. Vibratory stimulation reached 90% full-scale-range (FSR) when the hand reached the bounds of the visual display (corresponding to a displacement of 15 cm from the center). Vibratory stimulation reached 30% FSR at the near targets and 60% FSR at the far targets (corresponding to a displacement of 5 and 10 cm respectively from the center). In the second mapping, *error feedback*, the tactors encoded information about the instantaneous signed error between the hand and target locations. The vibratory stimulation was always 0 (i.e. tactors off) when the cursor was on the target. Vibratory stimulation reached 90% full scale range (FSR) when the hand was 15 cm from the desired target. In the third mapping, *sham vibration*, the tactors were cycled through a pseudorandom sequence that was matched in bandwidth and was irrelevant to the task at hand.

Participants trained on two tasks using the vibrotactile display: reaching and stabilizing. During the reaching task, participants performed out-and-back reaches to 16 targets. During the stabilization task, participants attempted to hold the robot handle steady at the center of the workspace against robotic perturbations. Detailed information about reaching and stabilization tasks, the experimental setup, and feedback encodings may be found in Chapter 3, which also describes the analyses applied to the reaching and stabilization portion of this experiment.

Participants performed the tasks under three different cursor visual feedback conditions and one target visual feedback condition. In the first condition (continuous cursor visual feedback; V_+), a 0.5 cm radius cursor was always visible on the computer screen and tracked the motion of the hand continuously. In the second feedback condition (no cursor visual feedback; V_-), participants attempted to track the target without ongoing cursor feedback (i.e., the cursor was never visible). In the third visual feedback condition (cursor Knowledge of Results; V_{KR}), participants only received cursor feedback of hand position after the trial was complete. The fourth visual feedback condition affected the target; here, the tar<u>G</u>et (G) was only visible after the trial was complete for knowledge of results (G_{KR}). This feedback condition was used only during training and sham blocks of error feedback, in which the target information was encoded within the vibrotactile feedback (or implied to be encoded in the vibrotactile feedback for sham vibration). In all other cases, the target was continuously visible.

For the stroke participants, I was concerned that longer session times due to slower task completion might induce fatigue. In order to reduce the time to complete the experiment, I simplified the protocol relative to the primary study. In particular, testing focused on the fundamental building blocks of movement needed for many activities of daily living (i.e., stabilization and goal-directed reaching) while the more complex tracking task was removed. During the first session, participants completed the V_+T_- familiarization for reaching and stabilization. For the second session, participants were given the choice to skip the familiarization block if they remembered the task. The participants then performed the reaching task twice with continuous vibrotactile feedback. During one session the vibrotactile feedback was error feedback, during the other it was state feedback; the order of feedback types was randomized across participants. Participants were provided visual feedback of the reach end point at the end of each reach to use for correction ($V_{KR}T_+$). Additionally, during the error feedback practice, the target was only visible at the end of each reach for use in correction (G_{KR}). The target was always visible during state feedback practice. In all other parts of the experiment the target was continuously visible. After the training blocks, participants performed the reach and stabilization tasks without any cursor or vibrotactile feedback (V_-T_-) to assess their baseline ability to complete the task using innate proprioception. Participants who scored low in proprioception (0 or 1) on the NSA (S02, S03, and S04) were allowed to skip this block if they became frustrated because the task appeared to be impossible for them to complete without visual or supplemental kinesthetic feedback. Next, participants completed the testing phase comprised of one reach task and one stabilization task with vibrotactile feedback and no visual feedback (V_-T_+). Lastly, the protocol included completing a reach task and stabilization task with task-irrelevant sham feedback; however most participants did not complete the sham vibration block due to time constraints or expressions of fatigue.

Two participants, S02 and S04, completed a preliminary exploratory session five months prior to the primary experimental sessions. During the preliminary sessions, participants experienced both error and state feedback while performing the reaching, stabilization, and tracking tasks. During the preliminary sessions, the patients were encouraged to "co-direct" the session by suggesting which task and tactor placement changes would work for them better. The preliminary sessions provided proof of concept and helped refine the protocol. One participant (S02) volunteered to attend for two additional sessions to explore learning effects of using vibrotactile feedback. During the additional sessions, the participant repeated the protocol for error feedback.

5.3 Results

Participants in the chronic stage of stroke sampled a range of hemorrhagic or ischemic and right or left hemisphere strokes, were between 1 and 16 years post-stroke, and presented with a range of clinical scores (Tables 5.1, 5.2, 5.3). Some participants were higher functioning while others were lower functioning; participants scored between 6 and 57 out of 66 for motor ability in the impaired arm with the FMA (Fugl-Meyer Assessment, upper limb, sections A-D) and between 13 and 80 out of 91 for functional ability in the CAHAI (Chedoke Arm Hand Activity Iventory) (Table 5.2). They had a range of spasticity in the MAS (Modified Ashworth Scale), though typically low for the shoulder and elbow (below 2 out of 4, Table 5.2 MAS). Two participants had fairly good proprioception while the other three had impaired or absence of proprioception in the more-involved arm (Table 5.3 NSA-proprioception and Table 5.2 FMA section H). Most participants retained good vibration sensation at both the elbow and wrist in both arms (Fig 5.3 Tuning Fork). Though tuning fork scores were slightly reduced for most participants at 6 (≥6.5 is normal), only the less-impaired elbow score for S04 was substantially reduced at 4.5. All participants scored higher than 24 on the Mini Mental State Examination (MMSE).

All participants tolerated the vibration well with no complaints of discomfort or hypersensitivity. One participant, S02, reported mild sensitivity to higher intensity vibrations, saying they felt like “a bright light or a loud noise” and were “distracting”. All participants reported trying the vibrotactile feedback was a positive experience. Some participants experienced a difficulty in sensation at the default tactor locations, though this was typically improved, though not necessarily eliminated, with adjustments. Some participants described a reduction of vibration sensation over time, whereas others reported improvements in their vibration sensation. Most participants also experienced an increase in body awareness or alertness while using the supplemental kinesthetic feedback. All participants were able to understand how to use at least one of the vibration feedback encodings. Error feedback was easier for the participants to understand and use to complete the tasks. Some were able to use the vibrotactile information to control the arm more readily; others required more time and practice to begin doing so. There appeared to be a “priming” effect, in which participants who learned error feedback first struggled to use state feedback. All participants experienced difficulty with integrating visual and vibrotactile inputs and motor control. Performance trends with extended practice by S02 suggest performance improvements can be seen when participants practice and learn to use the feedback over multiple sessions.

5.3.1 Vibration sensation after stroke

As a group, the stroke survivors experienced various levels of success in feeling and distinguishing the tactors on the less-involved arm. For three participants, S02, S03, and S05, the vibration sensation was satisfactory for all tactors in the default location; participants could distinguish each tactor individually and could detect variations in intensity. The other two participants each experienced difficulty with one or another of the tactors at the default location. S04 had difficulty reliably feeling the upper arm tactor; this was not surprising considering she had a low tuning fork score (4.5) at the elbow. Because she could not feel the vibration well on the bicep, the tactor was re-positioned on the shoulder, approximately 3 cm distal of the acromion. In this location, perception of the vibration improved. After adjustment, this participant could feel vibration of middle and high intensities at all tactor locations but could not feel low intensity vibrations below about 25% FSR at any tactor. By contrast, S01 experienced interference between the external forearm tactor and the upper arm tactor, with the upper arm tactor exerting dominance over the external forearm tactor. Additionally the internal forearm tactor had to be applied with increased pressure in order for the participant to perceive vibration. Both of these issues were improved (though not eliminated) by slightly adjusting the upper arm and internal forearm tactors' positions.

Three of the participants (S01, S02, and S04) reported that they experienced *degradation* in vibration perception that occurred over time both within and between sessions. S01 reported she could no longer detect vibration in her external forearm after approximately an hour of practice during the second session, although she did not experience this in the third session. Similarly, after about an hour of practice with the vibrotactile feedback, S02 reported the tactors seemed to all vibrate at once or all shut off for a minute or two. S04 experienced intermittent fluctuations in sensation throughout the session. Partway through the session while discussing with the participant about her experience, the experimenter discovered the participant was no longer detecting the presence of the upper tactor vibration, which was fixed with a small adjustment in position. Periodically thereafter the experimenter would ask if she felt vibration in her shoulder, and after a couple minutes she would repeatedly answer no even though the experimenter had verified the tactor was indeed vibrating. Adjusting the tactor slightly or pausing the experiment would typically return sensation for a few minutes. Notably, this participant would not notice the loss of sensation until the experimenter drew her attention to it.

By contrast, two of the participants reported *improved* vibrotactile perception between sessions. Both participants, S02 and S04, attended a preliminary pilot testing session 5 months prior to attending the multiple sessions reported here. S04, who had some difficulty to perceive low intensity vibrations below 25% FSR, also struggled to perceive the middle intensities (below 50% FSR) during the initial exposure session 5 months earlier. When she returned for the second session, her perception had improved and she could feel the middle intensities well (although she still struggled to detect low intensities below 25% FSR). S02, who completed 6 sessions in total, reported big differences in her impaired arm's perception between the second and third sessions. She reported an increased awareness of her impaired arm and said she was attempting to use her impaired arm in more daily tasks at her home.

Additionally, S03 became more alert while using the vibrotactile feedback; he sat more upright, interacted more with the experimenter, initiated conversation, and was attentive to his surroundings in between blocks. These observations are consistent with a vibration tolerability study in stroke survivors (Bento et al., 2012), in which vibration of various intensities was applied continuously to the wrist and ankle of five stroke survivors for a duration of five hours. Four of the participants had higher body awareness on the side of the stimulus or higher alertness during the five hours of stimulation and none experienced adverse reactions. All of the stroke survivors in Bento's study tolerated the vibration well without discomfort, like our stroke survivors. Likewise, our stroke survivors showed similar variation among participants and sessions as our healthy participants did. In both groups some participants experienced interference and differences in perceived strength between tactors, while some perceived the vibration well in the default position. Future work will need to pay attention to and accommodate for perceptual differences between individuals, along with specific perception needs arising from individual stroke pathologies (e.g. impaired vibration perception at the elbow for S04).

5.3.2 Contending with multi-modal sensory inputs

Four of the five participants described difficulties integrating simultaneous visual and vibrotactile inputs (S01, S02, S04 and S05). Three of them (S02, S04, S05) reported that it was easier to understand and complete the task without the visual feedback of the cursor. Specifically, S02 choose to close her eyes while reaching with vibrotactile error feedback, and we were able to explore this more during her fourth session. In earlier sessions, she had chosen to close her eyes while using vibrotactile error feedback. In the fourth session she agreed to try the test block once with her eyes open and once with her eyes closed to compare them. The participant said it felt like a totally different task when she looked at the target instead of closing her eyes. She said it is like a dual task since she must attend to both vision and vibration. She felt that having only 1 input was better and that the task was more tiring when she also used vision.

Similarly, she also felt disturbed or bothered if she felt a touch on her arm during the task (as occurred when I re-adjusted a tactor's elastic band when it had slipped). S04 choose not to look at the screen while using vibrotactile error feedback, once she had learned the concept. For S05, I initially demonstrated the vibration to her while the cursor and target were visible, but found that she grasped the concept more immediately and easily once we removed the visual input. S01 appeared to exhibit visual dominance: when reaching with visual and vibratory feedback, her movement would sometimes be in the direction that visually seemed correct, even if the vibration indicated otherwise. For example, if the next target appeared above the previous target but below the actual hand location, she might move upwards according to her visual input despite the vibration input indicating she should move down.

5.3.3 Cognitive and Sensory Motor Interactions

Two participants made comments about the difficulty of using vibrotactile feedback to control their moving arm, and about the difficulty of dividing attention between feeling the vibration on the one hand (and arm) and executing movements with the other. During the first session for S02, the participant mentioned that she understood the vibration, but could not yet transfer what she learned from the vibration to her movement. She suggested it was “as if my brain does feeling vibration and moving arm separately" and she described that it was hard to apply one to the other. Interestingly, this participant reported that her mental focus was on feeling movement in her impaired arm because of previous physiotherapy training. This participant suggested that it could have been easier to focus her attention on the sensation of vibration instead of the residual sensation of movement within her more involved arm if she had started using the vibration in the early stages of recovery from her stroke, as perhaps then she could have learned to focus on the supplemental feedback too. In later sessions, however, the participant said her ability to use the vibration while reaching had improved, and that she could now reach based on the vibration.

Interestingly, stabilization did not appear to become easier for her. S02 described the stabilization task as hardest for her because she "focused on movement in her impaired arm and didn’t pay as much attention to the vibration sensations". During the fourth session, I explicitly asked S02 to repeat the stabilization while trying to focus more on the vibration. She reported it felt like using a totally different part of her brain; one part does movement of the arm and a separate part feels vibration, and if she pays attention to the vibration she is missing some things about the moving arm. S04 also commented that she paid attention mainly to the vibration rather than to her moving arm.

S03 also had initial difficulty to apply the vibration to his reaching, but then developed a cognitive strategy to use the vibration. During the first session, using state feedback, this participant reported that the vibrotactile information "went the wrong way"; he moved the more impaired arm left and felt the corresponding left tactor, but couldn’t yet reverse the flow of information to feel the vibration and then transfer that information to control the arm. During the second session, using error feedback, he improved in his ability to apply the vibration to his reaching actions. Unprompted by the experimenters, he developed and explained a cognitive strategy to independently and sequentially resolve performance errors along each cardinal axis of vibration. First, he would make left to right movements until he located the area in which the left and right tactors were at a low intensity. Then, he would move the hand out-and-back until the y-axis tactors were also at a low intensity. If needed, he repeated the left-right movements to correct for error accumulated during the out-and-back movements because he couldn’t make completely straight trajectories. As determined during clinical assessments, this participant had trouble performing extension movements at the elbow and impaired fine motor movements. These deficits impaired his ability to execute straight-line motions, although he indicated verbally what he was trying to do.

By contrast, S05 was able to use the vibration to improve performance of the reaching task within the first few minutes of exposure - the fastest of any of our stroke survivor participants. This participant understood the concept easily and was able to begin using the vibration to guide her reaches within the first few targets. However, she experienced some memory difficulties that limited her use of the vibration for ongoing arm control. While the x-axis (left and right) tactors were easy for her, she sometimes forgot the appropriate interpretation of the y-axis (out and back) tactors. She would occasionally become confused and ask the experimenter to describe again "what the hand tactor meant". Discussion with the participant revealed she was not confusing the directions that each tactor represented, but rather that she was confused about feeling vibration at her hand and what the point of it was.

5.3.4 A possible confound of "priming" of State vs. Error feedback

Two of the participants (S02, S04) exposed to error feedback prior to state feedback had difficulty learning the state feedback method. S04 completed the error feedback session first, and then completed the state feedback session. During the state feedback session, she initially understood the idea of state feedback, however, she appeared to become confused at the near targets and started interpreting the vibrations as error feedback again. Though the participant did not elaborate on her interpretation at the near targets, she did indicate that she struggled to comprehend how to use the state feedback. Because she experienced difficulty feeling low intensity vibrations below 25% FSR, she felt little vibration at the near targets, which are located at 30% FSR; to this participant, the near targets had the lowest intensity vibrations she could feel. I speculate that this may have confounded S04's ability to differentiate between state and error vibrotactile feedback as she moved outward from the center. In light of the previous exposure to error feedback, state feedback in this situation could have been plausibly misinterpreted as indicating that she had moved too far (i.e., as error feedback)

S02 completed a preliminary exploratory session with error feedback five months prior. Upon returning for the primary experimental sessions, she completed a state feedback session and then an error feedback session. In spite of the five month gap, S02 persisted in interpreting the vibratory signals as error feedback, even after explicit instruction during the state feedback session. Even despite 20 minutes of reaching practice and explanation of how the state feedback should work, she kept attempting to employ the vibrotactile control strategy she had used for error feedback. The consequence of this conceptual confound was that her reach end points for all targets clustered on the center target (Fig 5.1).

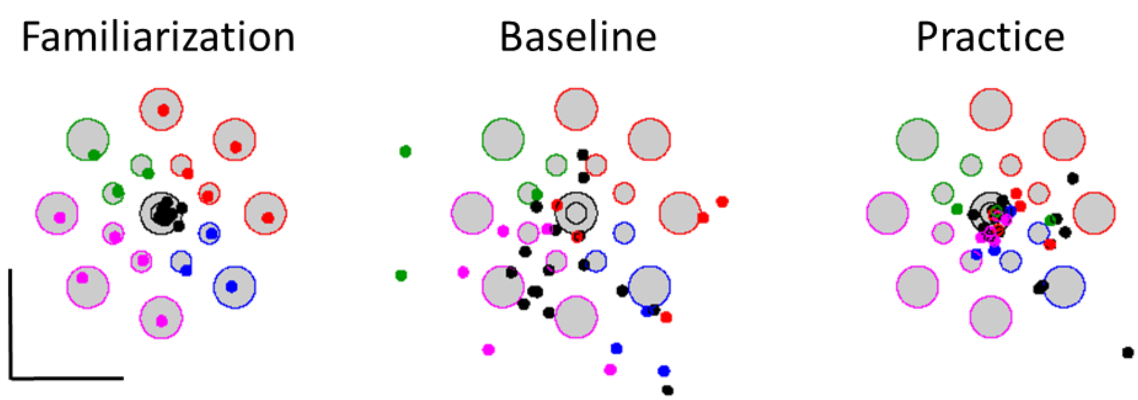

Figure 5.1: S02 reaching with state feedback. Good performance in familiarization (V_+T_-) shows she understands and can complete the task. Poor performance in the baseline (V_-T_-) shows she has impaired proprioception. During training ($V_{KR}T_+$) with state feedback (Practice), she persisted in trying to use the state feedback as error feedback (i.e. seeking the location with no vibration) resulting in a clustering of reach end points at the center target. Light grey circles are the

targets. Small colored dots are the end points. Each color corresponds to a quadrant and black corresponds to the center. Black scale bars represent 10 cm.

The two participants who were exposed to state feedback before error feedback did not experience difficulties learning the second feedback method. S01 understood not only how to use state feedback for the center but also grasped the correlation between the outer targets and the vibration intensity. When she was subsequently exposed to error feedback she easily understood how she should re-interpret the vibratory feedback to perform the task. S03 also easily learned error feedback after state feedback, understood that it was different, and found error feedback easier to use.

5.3.5 Learning over multiple sessions by S02

I invited S02 to return for two more sessions to explore increased practice with the supplemental error feedback. I selected this participant due to her willingness to participate, her interest in the vibrotactile feedback, and because she demonstrated excellent physical and cognitive ability when practicing the tasks. Each session lasted about one hour, and in each session, she received error feedback (Table 5.4 Error). During the additional sessions she improved in her reaching performance, and this was particularly true for the center target (Fig 5.2). Trial endpoints were increasingly clustered about the desired, center target as practice progressed. Within and across the sessions, S02 reduced the distribution of the end points (i.e. the area of the 95% confidence bounds ellipse) from 223 cm^2 to 86 cm^2, a 63% reduction (Fig 5.3 A). The end points are distributed primarily along the X axis, with less variation along the Y axis. The average absolute error was also reduced within and across sessions, from 3.6 cm to 0.84 cm, a 76% reduction (Fig 5.3 B). The average absolute error at the center target also decreased with each practice attempt. The values of around 0.8 cm during the third session were less than the 1 cm target radius. Even though her reach endpoint distributions exceeded the dimension of the central target, S02 successfully shifted the distribution of the end points to be centered over the center target by the end of training. These important data show that S02 was able to reduce both the systematic and variable target capture errors while practicing with the vibrotactile feedback.

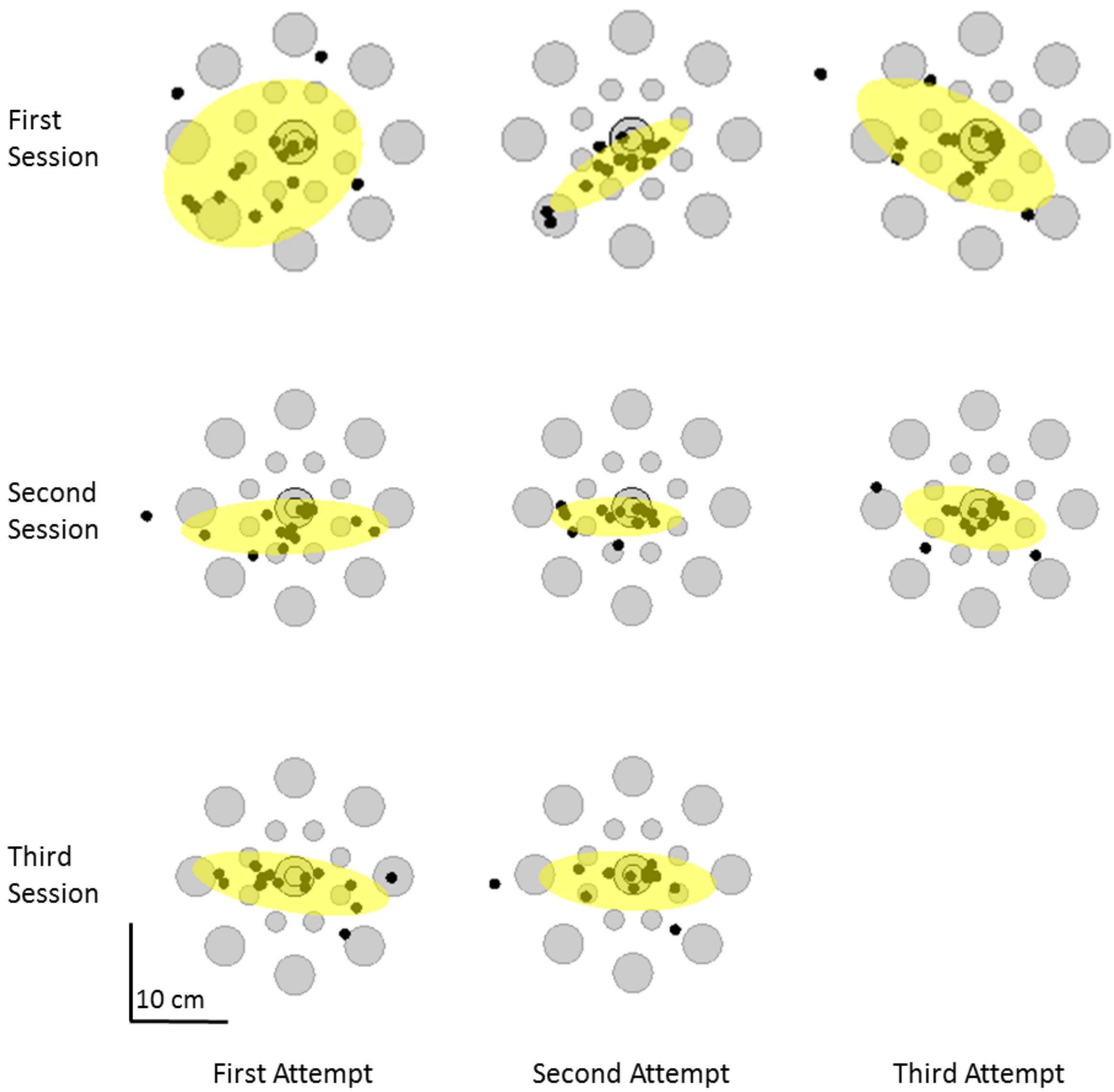

Figure 5.2: The center reaches improve with practice with error vibrotactile feedback, both within sessions and across sessions. Gray circles are the targets. Black dots are the end points of

the reaches to the center target. Yellow ellipse is the 95% confidence bounds of the end points. Data shown is during the practice block ($V_{KR}T_{+}G_{KR}$) using error feedback.

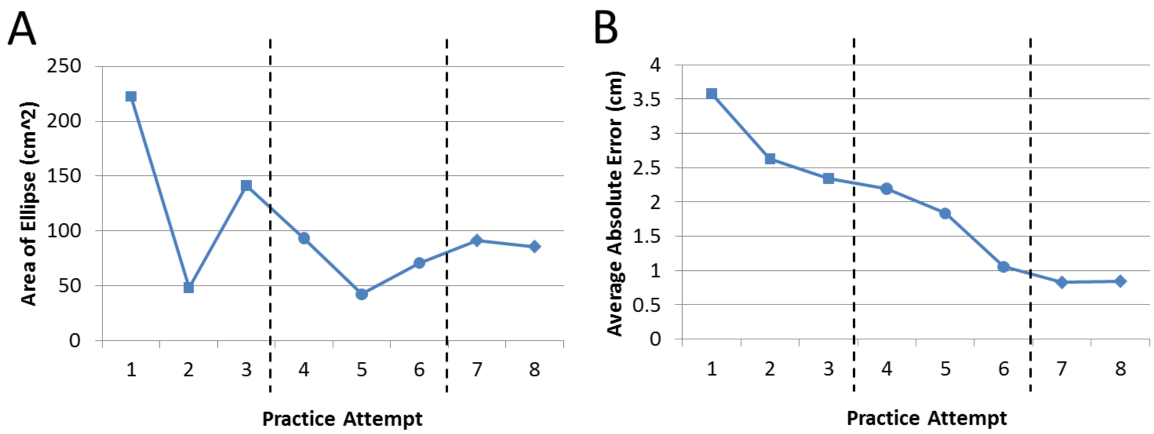

Figure 5.3: Improved performance of a stroke survivor practicing error feedback for three sessions. Vertical dashed lines indicate each day. A) Improvement in the distribution at the center target with practice. B) Improvement in the average absolute error at the center target with practice.

Practice with error vibrotactile feedback also improved peripheral target performance (Fig 5.4). Although few reaches ended with the hand on the corresponding target during either session, there was an improvement during the third session of more end points being in the correct quadrant. In particular, the upper left quadrant appears most improved (Fig 5.4 A, shown in red). The degrees of error between the end point and desired target (relative to the center) shows a modest improvement from 54°±11° to 39°±6° (p=0.06). The variability within sessions also modestly decreased from 47°±11° to 38°±2° (p=0.09).

It is likely that we observed the strongest performance improvement at the center target simply because the participant practiced the central target to a much greater extent than the peripheral targets. Because the reaching task was 16 out-and-back reaches, each peripheral target was only visited once within each block, whereas the center target was visited 16 times in each block. Taken together, the data from S02 support the supposition that stroke survivors can learn to use vibrotactile feedback to improve reach performance with extended practice.

Multiple practice sessions and repetition of the same target both increased her ability to use supplemental kinesthetic error feedback.

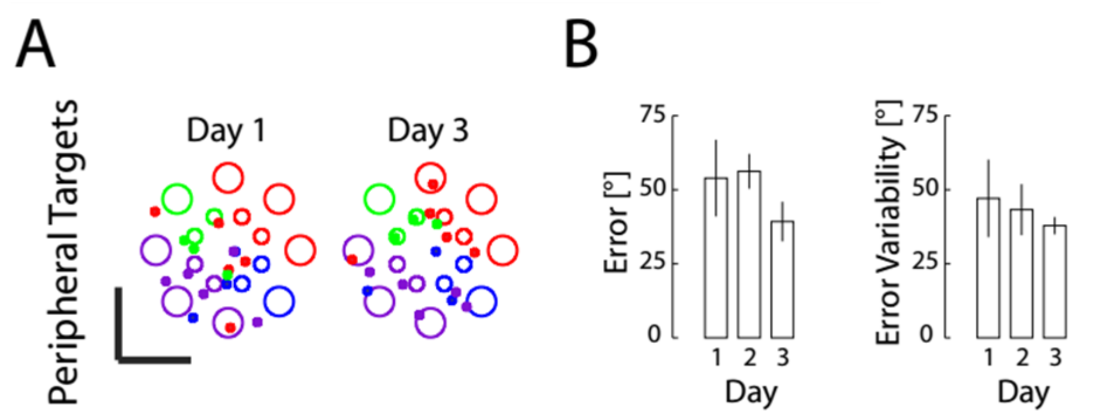

Figure 5.4: Peripheral target performance improved slightly with practice across days. Black bars represent 10 cm. (A) Performance at the peripheral targets improved slightly with training; in particular the upper left quadrant shown in red had the most improvement. Each color corresponds to a quadrant, hollow circles are the targets, and dots are the corresponding end point. D) The mean degrees of error about the origin (i.e. center) between the end point and the target decreased with practice. The mean and standard error of the variability of degrees of error of the end points decreased with practice.

5.4 Conclusions

All five stroke survivor participants came to understand how to use at least one of the vibrotactile feedback encodings, suggesting that supplemental, vibrotactile, kinesthetic feedback can indeed improve the performance of at least some stroke survivors with practice. Although some participants experienced difficulty integrating visual, vibrotactile, and motor inputs, multi-session practice in one participant suggests this may improve with practice. Our results appear to favor error feedback over state feedback as participants opined that it was easier to understand and use. However, it is important to note that participants who learned error feedback first may have been subject to an apparent “priming” effect, in which they struggled to use state feedback after receiving error feedback. The tentative comparative results presented here must therefore be taken with a grain of salt. A larger sample size is needed to practice with state feedback, without error feedback priming, in order to understand the extent to which stroke survivors can use, or learn to use, state feedback.

The mechanisms of learning to use vibrotactile feedback are not yet understood, for either healthy participants or stroke survivors. The learning seen in the multi-day practice with S02 could be due to the recruitment of closed-loop control pathways or due to cognitive control strategies or some combination of both. Future studies should investigate the cognitive or sub-conscious ways in which participants learn to use the vibrotactile feedback. Ultimately, training with the vibrotactile feedback seeks to reduce reliance on cognitive strategies, thereby minimizing the cognitive fatigue some participants described. Additionally, reducing the cognitive load would make this technology easier to use and more practical for applications beyond the lab, where users must also attend to the external and uncontrolled environment. Future studies should also investigate the extent to which practice can enhance performance of the stabilization task, i.e., to determine the extent to which extended practice with supplemental kinesthetic feedback can also enhance limb position stabilization control actions.

In conclusion, the results presented here in a small cohort of participants suggest that many stroke survivors can perceive vibrotactile stimulation applied to the less-involved arm, can come to understand how to interpret it to control goal-directed behaviors performed with the more involved arm, and that performance improvements in reaching are seen across multi-day practice sessions. Future multi-session learning studies will need to be conducted to extend these results to a larger cohort of stroke survivors, to isolate priming effects, and to allow participants the time to develop the skill needed to integrate the supplemental kinesthetic feedback into ongoing control of the arm and hand while performing real-world tasks in unstructured environments. We are encouraged in this goal because all stroke survivor participants found the vibrotactile feedback to be a positive experience, and some even seemed to experience secondary benefits in terms of alertness or body awareness. Such outcomes, if replicated in a larger cohort of stroke survivors, would be encouraging for the use of vibrotactile feedback devices moving forward. Thus, the present study demonstrated proof of concept for the use of the vibrotactile feedback to improve reaching performance in stroke survivors.

Chapter 6: Summary and Conclusions

As a first step toward the larger goal of reducing the negative impact of post-stroke kinesthesia deficits, this study tested the ability of people with no known neuromotor deficits to control goal-directed actions using various supplemental vibrotactile stimuli that provided real-time feedback about the moving arm to the other, non-moving arm. In a series of experiments, I determined that reaching and stabilization performance does vary systematically with the type of information encoded into optimal limb state vibrotactile feedback. I determined that both limb state feedback and goal-aware error feedback reduce the error in reaching and stabilization tasks. The tracking task, intended to assess the sensorimotor limits of using supplemental vibrotactile feedback to control the arm, did not successfully allow for a comparison of state and error feedback sensorimotor limits. With the recommendations provided, future studies may reattempt this task and quantify the control limits of each type of vibrotactile feedback.

While error feedback provided greater reaching and stabilization performance benefits than state feedback, it has challenges for implementation that state feedback does not. Based on the results, error feedback ultimately provides the best performance benefits for the long-term goals of the study; however state feedback also improves performance and is readily implemented outside of the laboratory, unlike error feedback, so should not be discounted for future applications. As a second step, I conducted a set of case studies examining the extent to which stroke survivors could use (and learn to use) supplemental vibrotactile feedback to enhance control of the contralesional arm. Our stroke survivors all tolerated the vibrotactile feedback well and were able to perceive and understand at least one of the state or error feedback encodings. With only one session of practice with each encoding, our stroke survivors struggled to integrate visual, vibrotactile, and motor inputs in order to use the vibrotactile information to control the arm. Two additional practice sessions with error feedback for one participant led to a two thirds reduction in reaching error. These results suggest stroke survivors can learn to use supplemental vibrotactile feedback to enhance control of the contralesional arm.

6.1 Future Directions

In working with the participants of the experiments, I identified a gap in vibrotactile literature. We do not currently have a standard test to assess perception and discrimination when more than one vibration site is used. Such a test would allow researchers and clinicians to understand and detect problems with interference between tactors, differences in perception at different tactors, and determine whether the participant can adequately perceive vibrotactile devices. My results suggest some users require custom tactor locations or may benefit from other adjustments (e.g. adjusting the upper or lower vibration threshold for stroke survivor participants S02 and S04). A test for these conditions would allow studies like this to standardize the conditions for satisfactory tactor perception, present standardized perception results for participants, and reduce one of the uncontrolled aspects of the current study. Such a test will require careful study of interacting variations across people, sessions, vibration amplitude and frequency, and location and pressure on the skin. Yet, it would open the gates for better-controlled studies in any field or application involving vibrotactile feedback.

Based on the results with the stroke survivors, a longer term study is required to understand the benefits of the vibrotactile feedback and state and error feedback encodings for stroke survivors. With only 1 hour of practice, our stroke survivors struggled to master the skills required to use the vibrotactile feedback to improve their performance. The improved precision and accuracy seen in the participant who attended for two additional sessions is proof of concept that stroke survivors can indeed learn to use vibrotactile feedback and can improve their performance using it with practice. Future longer-term studies can determine the extent to which performance can improve, as well as dosage and techniques to best train stroke survivors to use the vibrotactile feedback.

Future work should also investigate how vibrotactile information content is processed and integrated with other sensory inputs. Our stroke survivors experienced difficulties integrating multiple inputs and some stroke survivors and healthy participants indicated the use of cognitive strategies in processing and using the vibrotactile information. Ideally, we wish to encourage less cognitive strategies and emphasize sub-conscious processing of the vibrotactile information, in order to minimize the cognitive load and attention required to use the vibrotactile feedback in noisy and uncontrolled non-laboratory environments. Lieberman et al. (2007) reported that higher workloads when learning to use vibrotactile feedback do decrease with practice. Future studies should investigate the extent to which participants can learn to process the vibrotactile information content in a sub-conscious way, and if so, identify the mechanisms for such sub-conscious processing. For example, it is possible that vibrotactile feedback could become part of closed-loop control by feeding into the multisensory integration scheme described by Deneve and Pouget (2004). In their study, they proposed that integration involves “translation” of one sensory modality (and mapping) into another. This means that intact proprioception signals can be mapped to a virtual visual representation of hand position, and allow for satisfactory performance in the absence of visual feedback, as happened in the tracking task. Perhaps a similar sub-conscious approach could be learned for the use of vibrotactile feedback; in which the vibrotactile information could be mapped to a virtual visual representation of hand position, which in turn could be used to drive performance for stroke survivors in place of impaired or lost proprioception.

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